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NAVAL POSTGRADUATE SCHOOL

Monterey, California

9 Master's THESIS,

6 DEVELOPMENT OF A METHOD FOR MEASURING VELOCITY AT THE EXIT OF A COMPRESSOR ROTOR USING KULITE PROBES WITH SYNCHRONIZED SAMPLING.

by

10 Keith Allen Winters

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Thesis Advisor: R. P. Shreeve

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Development of a Method for Measuring Velocity at the Exit of a Compressor Rotor Using Kulite Probes with Synchronized Sampling		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; March 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Keith Allen Winters		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE March 1978
		13. NUMBER OF PAGES 120
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Kulite Probes
Compressor Rotor
Rotor blade passages
Velocity vector

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Development of a Method for Measuring Velocity at the Exit of a Compressor Rotor Using Kulite Probes with Synchronized Sampling

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
March 1978

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ABSTRACT

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I. INTRODUCTION

The work reported here is part of an on-going effort at the Naval Postgraduate School to determine the aerodynamic characteristics and performance of a single stage, axial transonic compressor (Fig. 1) using real time instrumentation.

In work already reported a multiple sensor pneumatic probe (Dodge probe) was developed to determine the average velocity at the rotor exit [Ref. 1]. The design of the probe was based on a knowledge of the characteristics of simple impact probes, and experience which had been gained in representing analytically the characteristics of multiple sensor probes [Refs. 2 & 3]. A new method of representing the characteristics of multiple sensor probes was developed and the time averaged flow from the rotor was measured [Ref. 4]. In order to obtain information on the flow within the rotor itself, real-time measurements were required. A synchronized sampling system was therefore developed which allowed programmable digital data acquisition from fixed instrumentation. [Ref. 5] Using this electronic "pacer," sampling and analog to digital conversion of transducer signals was controlled to be at any of 128 positions between any selected adjacent pair of the 18 blades of the rotor, independent of the speed.

A method of velocity measurement was proposed which used two Kulite probes with synchronized sampling. The technique would establish the

instantaneous and some time dependent properties of the velocity field in the frame of the compressor rotor. [Ref. 6] In addition it was proposed to relate the results obtained with this method to measurements made using hot wire probes and using laser velocimetry. The primary objective of the overall research effort was to understand and to interpret the phenomena occurring at different machine conditions. [Ref. 6]

The purpose of the present work was to begin the development of the proposed probe system to measure "instantaneous" velocity at the exit of the transonic compressor rotor. The ideas behind the two-probe technique were derived from the previous work on multiple sensor probes [Ref. 1, 2, 3&4] and the application of synchronized sampling. Conceptually the two probes can be considered to supply measurements which correspond to those of the sensors of a multiple sensor probe. The synchronized sampling allows measurements from two physically separated probes to be taken (at different times) at the same point in the reference frame of the rotor.

The initial step in the proposed method was to determine the yaw angle of the flow at any required point in the rotor frame. In the present work a method for determining the flow yaw angle at a point in the rotor frame using a single Kulite probe was developed and successfully tested in the transonic compressor.

Section II describes the methods used to obtain velocity from pressure measurements taken with a multiple sensor probe, and introduces the

proposed velocity measurement method and the method to determine flow yaw angle. In Section III the Kulite and pneumatic probes and the data acquisition system used in the current work are described. A technique for calibrating the Kulite probe on-line to an equivalent pneumatic probe was developed and the method for yaw angle measurement was verified in experiments using a steady, calibrated free jet. The tests and results are presented in Section IV. Section V describes the transonic compressor test conducted to determine the flow yaw angle at selected points in the rotor frame and discusses the results. Conclusions of the study are given in Section VI.

The use of an impact probe to measure yaw angle required that the characteristics of such a probe be known. Measurements of the characteristics of an impact probe were made in a free jet, and an analytical expression was found to represent the results. The analytical representation was fundamental to the successful measurement of the yaw angle, which followed. The measurements and analysis of the results from tests of a simple impact probe are given in Appendix A.

The derivation of a numerical procedure to approximate cylindrical probe characteristics with the empirical expression is given in Appendix B. Also described is the method used to derive yaw angle from probe data using the same empirical expression. Finally, the empirical expression was used to derive the calibration characteristics of the Dodge probe which was constructed using tubing similar to that used in the construction

of the test impact probe. The derivation is given in Appendix D. Appendix C describes the computer programs used in acquiring data.

II. APPROACH

A. USE OF MULTIPLE SENSOR PROBES TO MEASURE VELOCITY

The United Sensor five hole probe and the probe constructed by F. J. Dodge [Ref. 1], shown in Figure 2 can be used to measure air average velocity when the outputs of the multiple sensors oriented at various angles to the probe axis are calibrated over a range of Mach numbers and pitch angles. Yaw angle is first determined directly by balancing the outputs of the two sensors which are set at equal and opposite angles to the plane of the impact sensor and the probe shaft. Pitch angle ($\emptyset$) and non-dimensional velocity magnitude (x) are determined from readings taken after the probe has been rotated to balance the pressures at sensors P_1 and P_2 (Fig. 2), and the yaw angle has been noted from a vernier scale.*

The first method for calibrating and applying multiple sensor probes uses the definitions:

$$\beta = \beta(x, \emptyset) = (P_1 - P_{23}) / P_1 \quad \text{(United Sensor and Dodge)}$$

$$\bar{\gamma} = \bar{\gamma}(x, \emptyset) = (P_1 - P_4) / (P_1 - P_{23}) \quad \text{(Dodge)}$$

or

$$\bar{\bar{\gamma}} = \bar{\bar{\gamma}}(x, \emptyset) = (P_4 - P_5) / (P_1 - P_{23}) \quad \text{(United Sensor)}$$

*Footnote: The non-dimensional velocity x is defined as $x = V/V_t$, where V = velocity magnitude and V_t = "limiting velocity" = $\sqrt{2C_pT_t}$ for a perfect gas, where C_p = specific heat at constant pressure and T_t = stagnation temperature.

In the calibration, data for β and $\bar{\gamma}$ are measured in a controlled flow over the range of pitch angles and Mach numbers expected in the unknown flow to be measured. The data is then approximated to yield fifth order polynomial expressions for, $\bar{\gamma} = \bar{\gamma}(\phi, x)$ and $x = x(\beta, \phi)$. In application, probe measurements in an unknown flow are reduced to the velocity vector by solving the polynominals simultaneously. This method is described in Refs. 1, 2, and 3.

A second calibration method [Ref. 4] has been developed in which β and $\bar{\gamma}$ are defined as in the first method. Calibration data is obtained in a known flow and reduced to fifth order polynomial expressions for:

$$\phi = \phi(\bar{\gamma}, x)$$

$$\beta = \beta(\phi, x) \cdot \nu(x)$$

where $\nu(x) = (\gamma / \gamma - 1)\ x^2\ (1 - x^2)$

From these approximations, which include the primary dependence on velocity explicitly, readings of β and $\bar{\gamma}$ in an unknown flow are reduced to velocity magnitude and pitch angle as in method 2.

A third method uses an analytical expression for the characteristic behavior of a single cylindrical impact tube in yaw or pitch at different Mach numbers. The overall calibration for a multiple sensor probe constructed using similar tubing then can be derived analytically as shown in Appendix D.

B. MEASUREMENT OF VELOCITY USING 2 KULITE SEMICONDUCTOR PROBES WITH SYNCHRONIZED SAMPLING

Construction of sufficiently small multiple sensor probes using Kulite semiconductor sensors was not considered to be practical due to the small probe size required and the low probability that a probe could be constructed without the failure of at least one sensor. Moreover, such a probe could not be used to resolve peripheral variations in the yaw angle downstream of the transonic rotor.

What was proposed in Ref. 6 was to use two separate impact probes to perform the tasks of the separate sensors in the multiple sensor probe.

The two probes are located at different peripheral but identical axial and radial stations between the rotor and stator blade rows. The two probes are shown in Fig. 3. The probes are sampled under pacer control such that, at the time the two readings are digitized, the probes are at the same point in the reference frame of the rotor. [Ref. 6] A computer peripheral device which is required to control the data acquisition (pacer) was developed by West. [Ref. 5]

The 90^o or type A probe shown in Figure 3 can be rotated in yaw about the tip to angles corresponding to the sensors for P_1, P_2, and P_3 in the Dodge probe. The 55^o or type B probe shown in Figure 3 must be set at the balanced or zero yaw angle (determined using the type A probe) to measure the pressure corresponding to P_4 in the Dodge probe. To determine velocity, one of the three methods described in the preceding

section must be used to represent and apply the calibration. The two probes must be calibrated together in a steady uniform flow as if they were the sensors of a multiple sensor probe.

The initial step in applying the two probe system to measure velocity is to determine the yaw angle of the flow at the required point in the rotor frame. Only then can the two probes be set to angles at which the calibration was established. In the present work, a method for determining the yaw angle at each point in the rotor frame was developed using only the type A probe.

Since the method makes use of the characteristics of cylindrical impact probes, a preliminary investigation was made of the characteristics of *pneumatic cylindrical impact probes.* The results are given in Appendix A. It was found that the response of the probe could be represented as a pressure coefficient Cp, defined as:

$$Cp = \frac{P_p - P_t}{\frac{\gamma}{2} p M^2} = AM^{.01} \left[\sin^2 B (\Psi - \Psi_o) \right]^N$$

where

A, B and N are constants for the particular probe,

M = Mach number

p = static pressure

γ = ratio of specific heats

P_p = probe pressure

P_t = impact pressure

Ψ = angle of the flow to a reference scale

Ψ_o = angle of the axis of the probe to the reference scale

When the flow angle to the probe axis was a combination of pitch angle, ϕ, and yaw angle, α, then Ψ was calculated using the geometrical relationship:

$$\Psi = \cos^{-1}(\cos\phi \cos\alpha)$$

These results provided the basis for the development of a technique to derive yaw angle from Kulite probe measurements: the development is described in Section IV, following a description of the probes and data acquisition method given in the next section.

III. INSTRUMENTATION

A. PROBE DESCRIPTION

Figure 3 is drawing of the XB-062-25 semiconductor probes manufactured by Kulite for the tests conducted in this study. The sensors in each probe tip were standard CQ-052 series Kulite ultra miniature pressure sensors. Kulite Type "B" screens were installed on the probes to protect the sensors from particle impingement in high velocity flows. Figure 4 shows the probe tip dimensions and internal design.

Kulite-equivalent pneumatic probes were constructed at Naval Postgraduate School that were similar (to within 0.002 inches) to the external geometry of the Kulite probes shown in Figures 3 and 4. Initial impact pressure measurements taken with the Type A Kulite and pneumatic equivalent probes were consistently 10% below actual total pressure in the flow. It was immediately recognized that flow stagnation was occurring in the center of the probe face and not at the holes in the screen. Therefore, a shroud of 0.083 inch outside diameter, stainless steel tubing was added as shown in Figure 4. Subsequent tests indicated good agreement of impact pressure measurements with actual total pressure with no noticeable loss in the frequency response of the Kulite probe.

B. DATA ACQUISITION SYSTEM

Data acquisition from the Kulite probes and conventional strain gauge transducers was controlled by a Hewlet-Packard 21MX computer. A pacer

developed by West [Ref. 5] was used for "synchronized" sampling behind the transonic compressor rotor as shown in Figure 5. Synchronized sampling allows the properties of the flow to be determined at a point which is fixed with respect to the rotor. The pacer uses conditioned 1 per blade and 1 per rev signals to generate a trigger pulse at a selected location in the rotor frame. There are 256 equally spaced selectable locations in each rotor blade pair. Steady and nonsteady flow properties can be determined by sampling at a discrete location as many times as is necessary. Figure 6 shows the complete data acquisition system used in the present study. Appendix C is a discussion of the software used with the 21MX computer.

IV. PRELIMINARY MEASUREMENTS IN A FREE JET

A. INTRODUCTION

In order to use semiconductor probes for quantitative pressure measurements in an environment in which the temperature is unknown, a means of on line calibration must be used. The output voltage of the Kulite probe is linear with respect to the pressure difference across the sensing diaphragm. A typical Kulite calibration is shown in Figure 8. However, large shifts in output voltage due to temperature changes have been reported and were confirmed by Paige [Ref. 7]. For this reason, Kulite semiconductors have not been used for absolute pressure measurements in turbomachinery but have been used to measure the fluctuations in unsteady or periodic flows. In calibration tests conducted in a steady air flow early in the present work, these shifts of level of output were observed. Shifts in the slope of the output were also observed when the Kulite probe was rotated to a new flow angle. Therefore, a technique to calibrate the Kulite probe against a geometrically identical pneumatic probe, similarly oriented in the flow, using the computer on line, was developed.

The goal of the experiments described in this section was to develop the on-line calibration procedure and to verify, in steady flow, a method for measuring yaw angle in the compressor. A four inch free jet was

used to provide a known uniform flow field for the tests. The test apparatus is described in reference 8. The Kulite type A and the equivalent pneumatic type A probes were inserted in the flow to be two inches apart on opposite sides of the jet axis. The mounting apparatus allowed both probes to be pitched and yawed simultaneously and to be set to similar angles with respect to the flow direction. A Prandtl probe was used to monitor the jet velocity.

B. KULITE-EQUIVALENT PNEUMATIC PROBE TEST

Tests in the free jet, similar to those described in Appendix A, were conducted to establish the characteristics of the type A equivalent pneumatic probe with respect to yaw angle and Mach number. The range of Mach numbers surveyed was .4 to .6.

The results are shown in Figure 7. The pressure coefficient vs. yaw angle characteristics for this probe and the variation with Mach number were found to be qualitatively similar to those of the cylindrical impact probe reported in Appendix A. The coefficients A, B, N, and were successfully calculated as described in Appendix B. It is concluded therefore that the technique for calculating the zero yaw angle described in Appendix B could also be used with the type A probe geometry.

C. KULITE PROBE TESTS

1. Averaging Techniques

The first measurements from the Kulite probe in a free jet verified the high level of turbulence and unsteadiness which were known to be

present from earlier measurements. In order to investigate the characteristics of the Kulite probe with respect to yaw angle and Mach number, some method of averaging over a number of data samples was necessary.

The purpose of the first test therefore was to determine the effect of sample number and interval on the average measurement obtained from the Kulite probe.

At one test condition, three ten minute tests were conducted in which the techniques for sampling the Kulite probe were varied. During the tests, the Kulite equivalent pneumatic probe pressure was read at close intervals using a water column U-tube manometer referenced to atmosphereic pressure. The Kulite reference pressure was sensed by a conventional strain gauge transducer connected to and calibrated on one input channel of the A/D converter. The reference pressure was obtained at one minute intervals by recording the average 100 samples taken at 10 millisecond intervals.

In each of the three tests, a data point for the Kulite probe pressure was recorded at 1 minute intervals for a period of 10 minutes. Each data point consisted of taking the average voltage from a number of ensembles of samples taken at 10 microsecond intervals. The data for the methods used in the three tests is shown in the following table:

METHOD	SAMPLES PER ENSEMBLE	# OF ENSEMBLES	ENSEMBLE INTERVAL (SEC)	TOTAL TIME (SEC.)
1	100	1	-	1
2	1000	1	-	10
3	100	10	2	20

For each data point, the pressure was calculated using the average voltage from the Kulite probe and the recorded reference pressure as shown in the following section, C.2. The results are shown in Figure 9.

It can be seen that methods two and three gave acceptable accuracy whereas method one did not. The failure of method one was the result of high frequency turbulence in the free jet. Seen on the oscilloscope, the dominant fluctuations in the Kulite signal had a period of about two milliseconds, so that a sample duration of one millisecond could not give a correct time average. Method two was used in subsequent tests in the free jet.

2. Calibration Method

The need to calibrate the Kulite transducer to account for changes due to temperature, and for shifts in output slope which occurred when the probe was rotated in the flow, was stated in Section IVA. A calibration procedure was therefore developed in the free jet tests and subsequently applied in the measurement of yaw angle. The Kulite probe calibration used the assumption that the equivalent pneumatic probe measured

the time average of the pressure on the face of the Kulite probe when the two probes were similarly oriented in the flow. The calibration procedure was to apply a controlled pressure to the reference tube of the Kulite probe, then sample, (as described in Section IV C. 1) the pressure from the equivalent pneumatic probe, P_p, the Kulite reference pressure, Pr, and the Kulite output voltage. This procedure was repeated for a number of calibration points, changing the reference pressure for each point. The data was reduced on-line using a linear least squares routine to obtain the constant coefficients x_o and x_1 in the equation,

$$P_p - Pr = x_o + x_1 \overline{E}$$

where $\overline{E}$ was the average amplified output voltage of the Kulite transducer.

In subsequently applying the calibration, samples of Kulite output voltage were reduced on line to values of pressure, Pk, using the calibration coefficients x_o and x_1 in the equation

$$Pk = x_o + x_1 \cdot \overline{E} + Pr$$

An experiment was conducted to determine the minimum number of reference pressure settings required to calibrate the Kulite probe with acceptable accuracy. A calibration test was carried out, as described above, using eight different reference pressures. The coefficients x_o and x_1 were computed first using all eight data points. Then, using the same data, new coefficients were computed using various subsets of the eight data points. Table IV-1 shows the subsets used and the deviation of the

results from the eight point calibration. The results indicated that only small improvements in the accuracy were obtained by using more than two points. Two points, if properly chosen to include the range of expected pressures, gave a sufficiently accurate calibration. In subsequent experiments a two-point calibration was therefore used with atmospheric pressure as one reference pressure and the flow total pressure as the other.

D. YAW ANGLE DETERMINATION

The purpose of this experiment was to verify, in steady flow, a method of measuring the zero yaw angle behind the rotor of the transonic compressor using the type A Kulite probe. Measurements were made in the four inch free jet at Mach numbers of 0.406 and 0.587. At each Mach number both probes were set at pitch angles of -10°, 0°, and $+10^\circ$. At each pitch angle both probes were set at yaw angles of $\pm 60^\circ$, $\pm 45^\circ$, $\pm 30^\circ$, $\pm 15^\circ$, and 0° to the flow. After each change of angle the Kulite probe was calibrated as described above. Water column readings of the Prandtl probe and the Type A pneumatic probe were recorded, the Type A pneumatic pressure was sampled and the Type A Kulite average voltage was sampled and reduced on line to values of pressure.

In the off-line analysis, zero yaw angle was calculated from the data using the least squares method described in Appendix B. The number of points needed to determine the zero yaw angle was investigated by varying

the data points included in the least squares calculation. The results are given in Table IV-2 for 3, 5, 7 and 9 points.

It was seen that the zero yaw angle was determined to within 0.5 degrees for pitch angles of -10, 0 and +10 degrees. It was concluded that the Kulite probe, when carefully calibrated to an equivalent pneumatic probe, can be used to measure yaw angles with reasonable accuracy.

The need to calibrate the Kulite probe at each orientation was confirmed by an inspection of the calibration coefficients determined in the experiment. The coefficients are shown in Table IV-3.

The variation in the coefficients appeared to be sufficiently random in nature as to preclude any attempt to describe the change as a function of Mach number and flow angle. The variations were not understood, however, the technique of recalibrating at each angle was one which could also be applied in the compressor. It should be noted, however, that in the periodic flow behind a compressor rotor, application of the same calibration and measurement techniques will force agreement between the absolute values of the pneumatic time average and Kulite time average pressures.

(i) DATA

POINT	$P-P_r$ (ins. water)	AMPLIFIED KULITE OUTPUT (millivolts)
1	-42.8	-68.9415
2	-27.5	-46.193
3	-12.5	-25.2698
4	- 0.2	- 6.05109
5	24.2	29.0726
6	36.0	46.186
7	47.2	62.0352
8	57.8	77.7253

Impact pressure at the probe face, p_t=37.9 ins. water gauge.

Least squares fit to linear calibration given by, $P-P_r=\overline{x}_o+\overline{x}_1\overline{E}$:

$\overline{x}_o$=4.39565 ins. water, $\overline{x}_1$=686.358 ins. water/volt.

(ii) Least Squares fit to linear calibration, $P-P_r=x_o+x_1\overline{E}$, using subsets of points.

Points used for Subset	$(\overline{x}_o-x_o)$	$(\overline{x}_1-x_1)/\overline{x}_1$ (%)
1, 3, 5, 7	0.2	0.16
1, 4, 8	0.1	0.01
2, 4, 7	-0.1	-0.60
3, 4, 6	0.0	0.70
1, 3, 5	0.1	0.44
3, 5, 7	0.3	0.50
1, 8	0.2	0.07
2, 7	0.0	-0.51
3, 6	0.3	1.14
2, 5	-0.1	-0.36
1, 5	0.0	-0.10
2, 6	-0.1	0.39
3, 7	0.4	-0.07
4, 6	-0.2	-0.11

Table IV-1 Results of Kulite probe calibration in steady flow

P_k=Kulite pressure calculated using linear calibration

P_{ke}=Kulite equivalent pneumatic pressure measured with conventional transducer

$(P_{ke})_m$=Kulite equivalent pneumatic pressure measured with water column manometer

Entries in the table are the zero yaw angles (α_o), in degrees, calculated from the above measurements using subsets of the data recorded at a total of nine angles.

The subsets are as follows:

Subset #	Angles included
1	$0^o, \pm 15^o, +30^o, \pm 45^o, \pm 60^o$
2	$0^o, \pm 30^o, \pm 45^o, \pm 60^o$
3	$0^o, \pm 45^o, \pm 60^o$
4	$0^o, \pm 60^o$

Subset	No. of points	α_o from P_k	α_o from P_{ke}	α_o from $(P_{ke})_m$
		(M=0.406, ϕ=0^o)		
1	9	.70	.80	.81
2	7	.75	.80	.81
3	5	.82	.86	.86
4	3	1.31	1.29	1.33
		(M=0.406, ϕ=$+10^o$)		
1	9	1.38	1.10	1.08
2	7	1.40	1.11	1.09
3	5	1.48	1.15	1.14
4	3	2.09	1.61	1.60
		(M=0.406, ϕ=-10^o)		
1	9	.46	.60	.60
2	7	.49	.62	.60
3	5	.60	.65	.62
4	3	.78	.98	.89

Table IV-2 Calculated zero yaw angles from test described in Section IV-D.

Subset	No. of points	α_o from P_k	α_o from P_{ke}	α_o from $(P_{ke})_m$
		($M=0.587, \phi=0^o$)		
1	9	.86	.85	.85
2	7	.86	.85	.86
3	5	.95	.93	.92
4	3	1.33	1.47	1.44
		($M=0.587, \phi=10^o$)		
1	9	.91	.79	.83
2	7	.93	.81	.84
3	5	.95	.84	.88
4	3	1.38	1.17	1.25
		($M=0.587, \phi=-10^o$)		
1	9	.85	.77	.73
2	7	.85	.78	.74
3	5	.89	.82	.78
4	3	1.35	1.28	1.23

IV-2 (cont) Calculated zero yaw angles from test described in Section IV-D.

Probe Yaw Angle (Deg)	$\phi=0^\circ$ x_o	x_1	$\phi=-10^\circ$ x_o	x_1	$\phi=+10^\circ$ x_o	x_1
			(M=0.406)			
0	-3.9	696	-3.9	686	-5.8	685
15	-5.5	721	-4.2	694	-5.9	691
-15	-3.7	686	-5.2	691	-6.3	694
30	-2.6	683	-2.8	693	-5.1	690
-30	-5.0	689	-5.3	692	-7.4	691
45	-0.5	685	-0.2	689	-2.3	694
-45	-7.0	686	-7.4	698	-9.4	677
60	+4.5	715	+3.6	681	+3.1	679
-60	-9.3	711	-9.6	693	-12.4	671
			(M = 0.587)			
0	-4.8	689	-5.0	692	-4.5	685
15	-4.0	690	-5.0	694	-5.3	684
-15	-6.5	691	-6.1	689	-6.1	687
30	-3.5	692	-1.3	697	-3.8	681
-30	-9.1	692	-8.5	690	-10.0	691
45	-2.0	735	+5.5	684	+0.9	692
-45	-11.1	688	-12.6	685	-13.7	688
60	+16.1	673	+16.7	684	+16.3	672
-60	-20.0	697	-20.4	680	-19.6	659

x_o in inches water

x_1 in inches water/volt

Table IV-3 Variation of Kulite calibration coefficients in yaw angle test on the free jet.

V. FLOW ANGLE MEASUREMENTS IN A TRANSONIC COMPRESSOR

A. TRANSONIC COMPRESSOR

The transonic compressor is shown in Figure 1. It is driven by an air turbine drive unit capable of supplying 450 horsepower at 30,000 RPM. When operating at the design point, the relative Mach number at the rotor blade tip is 1.5. The flow rate is controlled by an electrohydraulic rotating throttle plate located at the inlet duct, which also contains a filter and flow measuring nozzle. An Allis-Chalmers multistage axial compressor supplies the turbine drive air. A complete description of the test facilities is given in reference 8.

B. PROBES AND INSTRUMENTATION

A Kulite type A probe, a pneumatic type A probe (Fig. 3), and the Dodge probe (Fig. 2) were inserted into the compressor at an axial distance of 0.65 inches (.31 chord lengths) behind the rotor trailing edge. A similar probe installation is shown in Figure 10. The radial displacement of each probe tip from the case wall was 0.9 inches. The three probes were separated peripherally at 45^{o} intervals.

The pneumatic connections to the Dodge probe P1 sensor and to the pneumatic type A probe are shown in Figure 11. The pneumatic pressures were sensed by conventional differential strain gauge transducers referenced to atmosphere.

The two strain gauge transducers and the Kulite type A probe transducer were connected through conditioning circuits to separate input channels of the high speed data system shown in Figure 6. The two transducers were calibrated using a water column manometer as a standard. The calibration coefficients obtained were used in the on-line program to reduce the transducer voltage outputs to pressure in inches of water gauge. A control program was written and used with the program "DATACQ" to acquire data during the tests. These programs are described and listed in Appendix C. On-line calibration of the Kulite transducer was an integral part of the experimental procedure.

C. TEST PROCEDURE

The compressor was stabilized at the desired operating condition and steady state performance data were recorded. The Dodge probe was rotated to balance the pressures at sensors P2 and P3 and the yaw angle, $\bar{\alpha}$, was recorded. This angle, $\bar{\alpha}$, was taken as a reference angle for the Type A probes. The pneumatic and Kulite Type A probes were rotated together to the following angle settings, in turn: $\bar{\alpha}, \bar{\alpha} \pm 30^\circ$, $\bar{\alpha} \pm 45^\circ$ $\bar{\alpha} \pm 55^\circ$. At each setting, the following procedure was carried out:

1. The Kulite probe output was sampled in Pacer "Free Run" mode. 1681 samples were taken at 10 microsecond intervals, the average was calculated and reduced on line to pressure.
2. The pressure at the P1 sensor of the Dodge probe and the pneumatic equivalent pressures were sampled.

3. Kulite output was sampled in a survey at 128 locations across blade pair 2 using synchronized sampling. Each location was sampled 10 times, (on successive revolutions) and the average of the 10 samples was reduced on line to pressure.

4. The pressure survey data were displayed on the HP 9862A plotter and stored in the HP9768 mass memory system.

5. Steps 3 through 5 were repeated for blade pair 8.

Data recorded during the test are given in Table V-1. Plots of the data obtained by synchronized sampling are shown in Figures 12 and 13. The synchronized data was observed to agree qualitatively with oscilloscope traces of the Kulite output voltage.

D. DATA REDUCTION TO FLOW ANGLE

The data from seven angles were used to calculate a zero yaw angle for each discrete location within the blade pairs, using the method described in Appendix B. The BASIC program "KAW78" used to reduce the data is listed in Table V-2.

E. RESULTS AND DISCUSSION

The distributions of the zero yaw angle for the Kulite probe (the yaw angle of the flow relative to the axial direction) for blade pairs 2 and 8 are shown in Figures 14 and 15 respectively.

In both figures, the wakes of the rotor blades are evident, and fluctuations are seen to be present outside of the wakes. It should be noted that

the shape of the observed angle variation through the wake would be the result, qualitatively, of the flow velocity being non-uniform in magnitude but at a constant angle relative to the rotor. The fluctuations outside the wakes are not understood. They are seen to be more definite in blade pair 2 than in blade pair 8. Further analysis of the data and more data at different test conditions are needed to determine the accuracy of the detail which is evident in Figures 14 and 15.

The numerically averaged yaw angles for blade pairs 2 and 8 were 22.8° and 22.5° respectively. The pneumatically averaged yaw angle obtained from the Dodge probe was 23.2°. The yaw angle calculated using time averaged pressures from the equivalent pneumatic probe was 22.2°. This agreement supports the magnitudes of the yaw angles shown in Figure 14 and Figure 15, for which no other verification is presently available.

Compgressor Performance Data

N = 18360 RPM

Weight Flow = 11.92 lb/sec

$T_{t1} = 76.1^{o}F$

P_{t1} = 389.7 inches water

Pressure Ratio (t-t) = 1.167

Efficiency (t-t) = 0.92

Data From Probe Measurements

Pressures in inches of water

Point	Blade Pair	Probe Angle (deg)	x_o in. (H_2O)	x_1 in. (H_2O/volt)	P_k-P_a	$P_{ka}-P_a$	P_1-P_a (Dodge Probe)
1	2	23.2	-4.02	702	55.0	56.2	56.4
2	8	23.2	-	-	56.9	-	-
3	2	53.2	-6.44	689	50.2	51.2	57.1
4	8	53.2	-	-	52.9	-	-
5	2	-6.8	-0.90	691	52.7	51.5	55.7
6	8	-6.8	-	-	51.3	-	-
7	2	68.2	-14.34	702	31.9	32.6	56.4
8	8	68.2	-	-	32.2	-	-
9	2	-21.8	2.20	684	37.1	37.2	56.6
10	8	-21.8	-	-	37.2	-	-
11	2	78.2	-14.77	666	18.8	19.8	56.0
12	8	78.2	-	-	19.7	-	-
13	2	-31.8	9.44	731	18.4	21.6	55.3
14	8	-31.8	-	-	19.1	-	-

TABLE V-1 TRANSONIC COMPRESSOR TEST DATA

```
10 REM KAW78 LEAST SQUARES CURVE FITTING FOR YAW ANGLE 3/16/78
11 REM ALSO HAS CP COMPUTING--
20 DIM A[3,50],T[20],PS[129,7],CS[129,7],BS[128]
21 FILES WANG2,CPBP8,WRAG2
22 MAT READ # 1;P
30 GOSUB 500
35 SCALE 0,130,-60,60
36 XAXIS 0,5,0,130
37 YAXIS 0,5,-60,60
38 J5=0
40 FOR J=2 TO 129
42 FOR I=1 TO 7
44 A[1,I]=P[1,I]/180*PI
45 A[2,I]=C[J,I]
46 NEXT I
50 GOSUB 130
60 PLOT J,YO*180/PI
65 PEN
70 PRINT J,YO*180/PI
75 B[J-1]=YO*180/PI
76 J5=J5+B[J-1]
80 NEXT J
85 MAT PRINT # 3;B
87 PRINT "AVG OF 128 SAMPLES="J5/128"  DEGREES"
90 STOP
101 NEXT I
105 FOR I=1 TO I5
110 LET A[1,I]=A[1,I]/R
120 NEXT I
130 LET K=1
140 LET A=-1.45947
150 LET B=1.07503
160 LET N=1.78747
170 YO=20/180*PI
180 LET S=0.00175
190 LET T[K]=0
```

TABLE V-2. BASIC PROGRAM "KAW78"

```
200 FOR I=1 TO 7
210 LET C9=COS(B*(A[1,I]-Y0))
220 LET C=A[2,I]-A*(1-C9↑2)↑N
230 LET B1=2*A*N*(A[1,I]-Y0)*(1-C9↑2)↑(N-1)*C9*SIN(B*(A[1,I]-Y0))
240 LET T[K]=C*B1*B/(A[1,I]-Y0)+T[K]
250 NEXT I
260 LET T[K]=2*T[K]
270 IF ABS(T[K])<0.00001 THEN 340
280 IF K<2 THEN 310
290 LET S1=T[K-1]-T[K]
300 LET S=T[K]*S/S1
310 LET Y0=Y0+S
320 LET K=K+1
330 GOTO 190
340 RETURN
350 STOP
500 FOR I=1 TO 7
510 C[1,I]=P[1,I]
520 NEXT I
530 FOR J=2 TO 129
540 L=0
550 S=S1=S9=100
560 FOR I=1 TO 7
570 IF P[J,I]<L THEN 590
580 L=P[J,I]
590 IF P[J,I]>S THEN 620
600 S=P[J,I]
610 I9=I
620 NEXT I
630 FOR I=1 TO 7
640 IF I=I9 THEN 680
650 IF P[J,I]>S1 THEN 680
660 S1=P[J,I]
680 NEXT I
690 FOR I=1 TO 7
700 C[J,I]=0.84*(P[J,I]-L)/(L-0.5*(S+S1))
710 NEXT I
720 NEXT J
725 MAT PRINT # 2;C
730 RETURN
```

TABLE V-2 (continued)

VI. CONCLUSIONS

In measurements made downstream of the transonic compressor rotor, there was found to be good agreement (better than 1%) between the yaw angle determined using a Dodge pneumatic probe and the average of the peripheral distribution of the yaw angle calculated from a system of Kulite probe measurements. It was therefore concluded that the technique to determine "instantaneous" yaw angle proposed here and verified in a steady free jet, also gave good results in the unsteady compressor flow field. The yaw angle variation in the rotor blade wakes was resolved and the results contained very little scatter. A weak periodic structure was detected across one of the two pairs of blade passages measured (Blade pair #2). More analysis of the data is required however, before conclusions can be drawn concerning the detail which appears to be present in the results.

The yaw angle measurement was a necessary step in the development of a method to determine the velocity field at the rotor exit from stationary instrumentation. The next step is to determine the best method for representing and applying the calibration of a two probe system. The fluctuations measured in the zero yaw angle (or turning angle) behind the transonic compressor rotor makes less attractive, but does not preclude, a calibration method that requires the type B probe to be set at the zero

yaw angle for each location sampled. However, an interactive computer-probe control system would be needed. Alternatively, a method based on the approach developed in Appendix D has potential for success if applied to the proposed two probe system. The multiple-sensor interference effects found in the Dodge probe, to which the method of Appendix D was applied, are not present in the two probe system.

The development of such a method would require that suitable expressions be found which would individually characterize the behavior of the type A and type B probes with respect to the Mach number, yaw angle, and pitch angle of the flow to be measured. The expression developed in this study was shown to characterize properly the behavior of cylindrical probes with respect to Mach number and yaw angle, but the dependence on pitch angle was not obtained explicitly.

Reasonable agreement was noted (Table V-1) between the magnitudes of the time averaged Kulite probe impact pressure and the pneumatically averaged impact pressure obtained using the Dodge probe. It was concluded that a Kulite probe, with on-line calibration to an equivalent pneumatic probe, can be used for quantative real time impact pressure measurements downstream of a rotor.

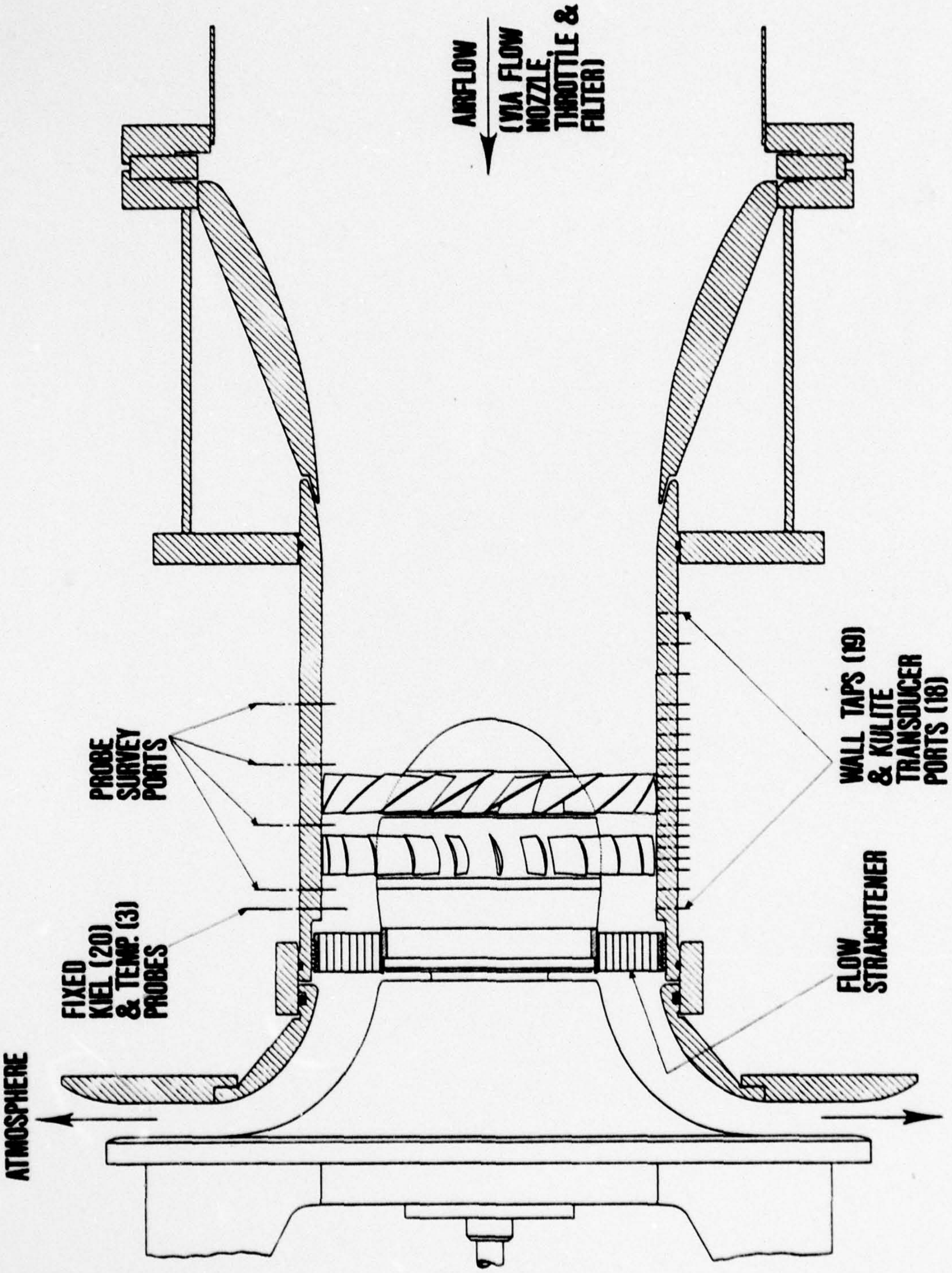


FIGURE 1. TRANSONIC COMPRESSOR

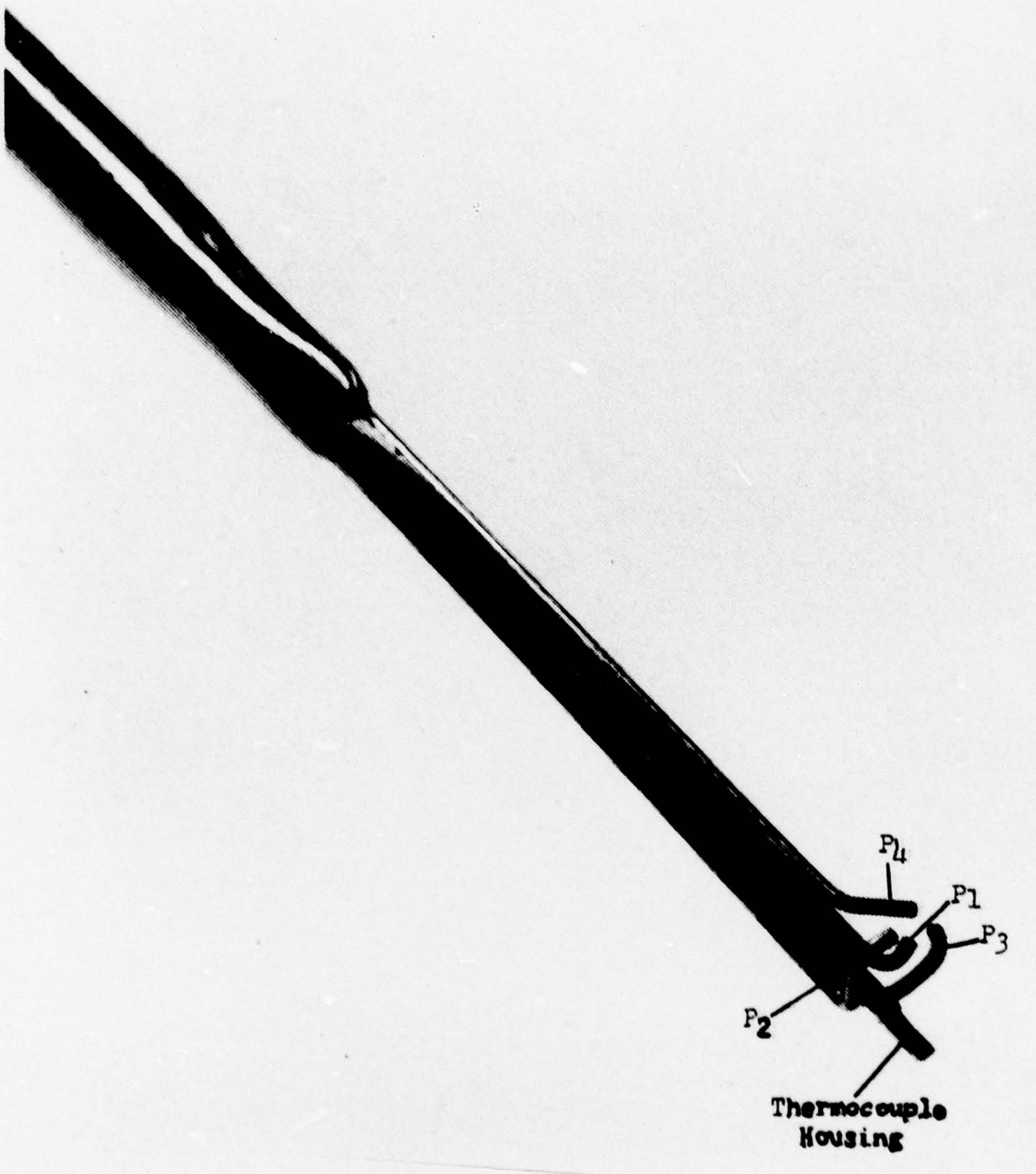


FIGURE 2. DODGE COMBINATION PROBE PHOTOGRAPH WITH THERMOCOUPLE REMOVED

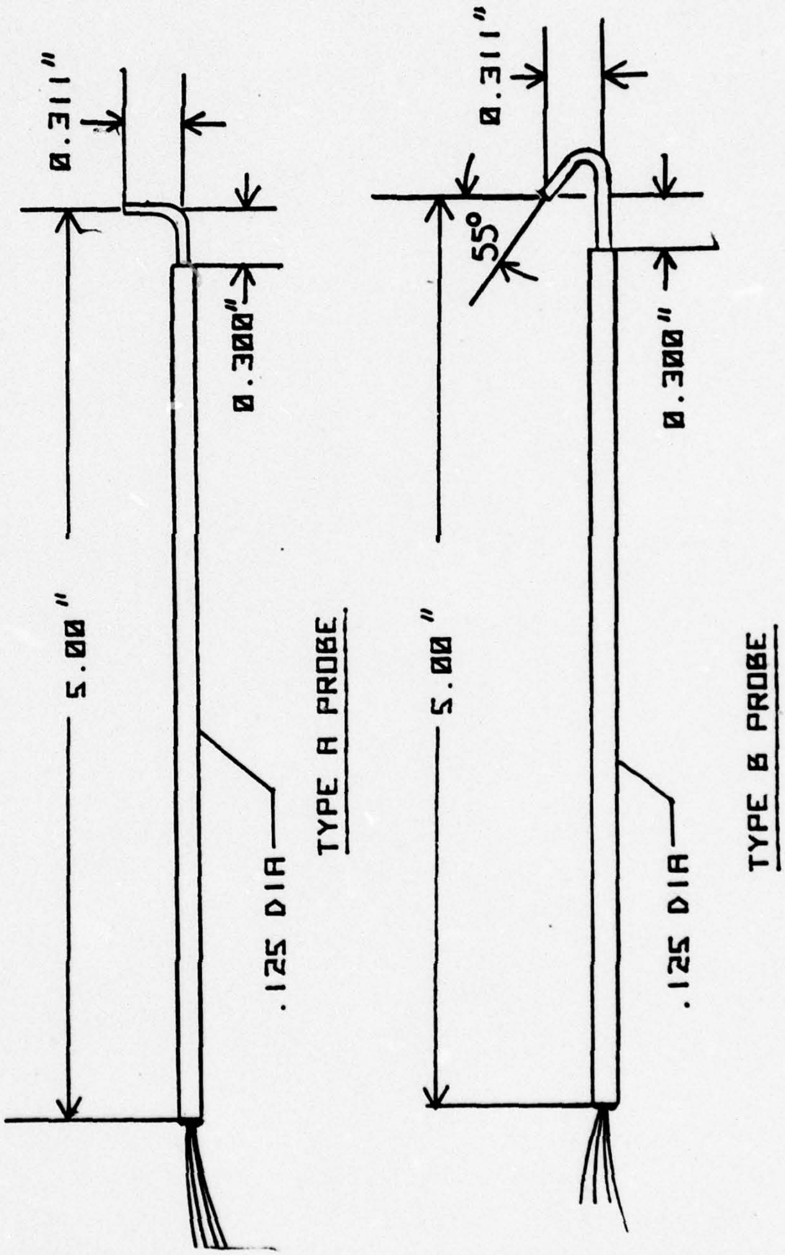


FIGURE 3. KULITE PROBES

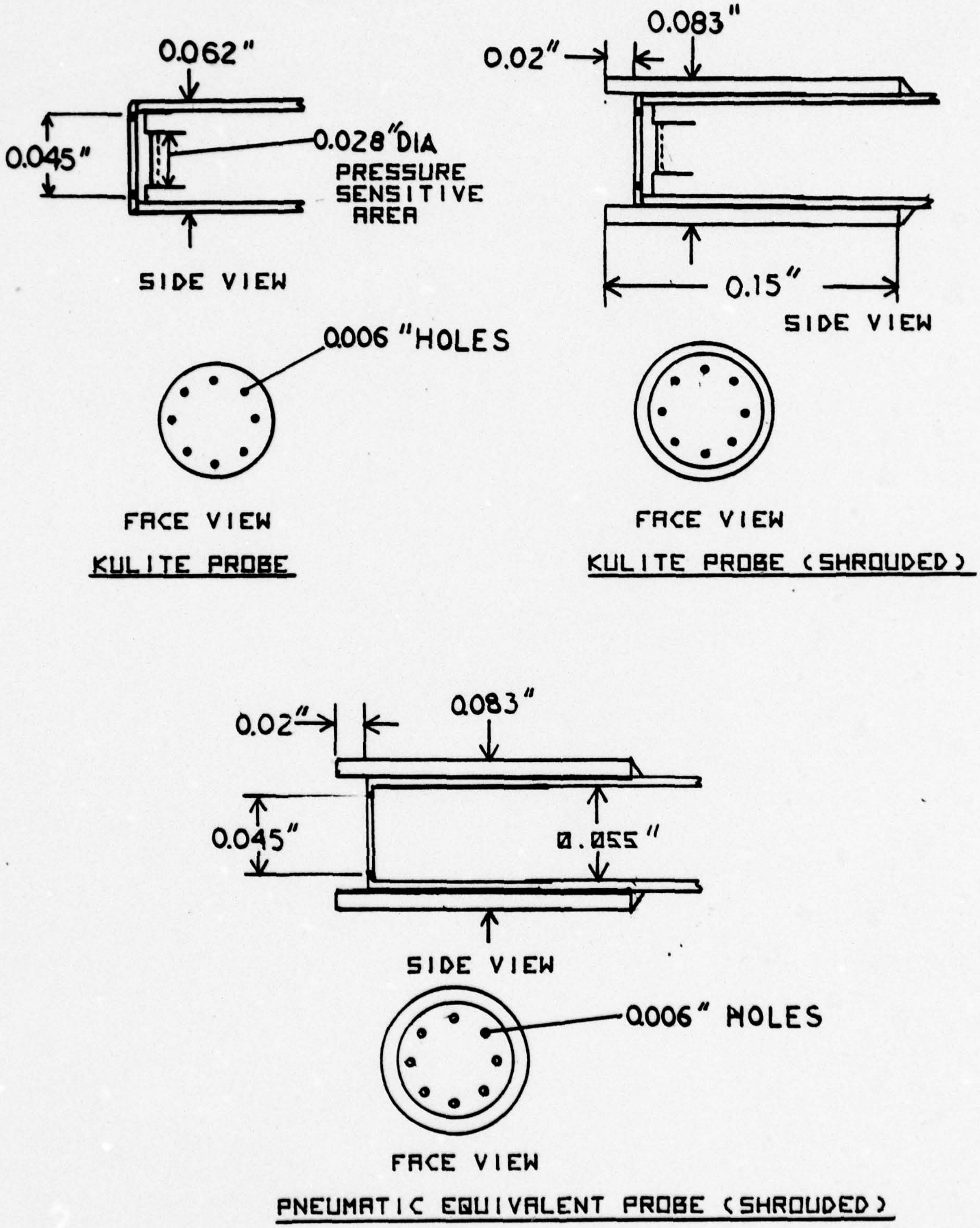


FIGURE 4. PROBE TIP DETAIL

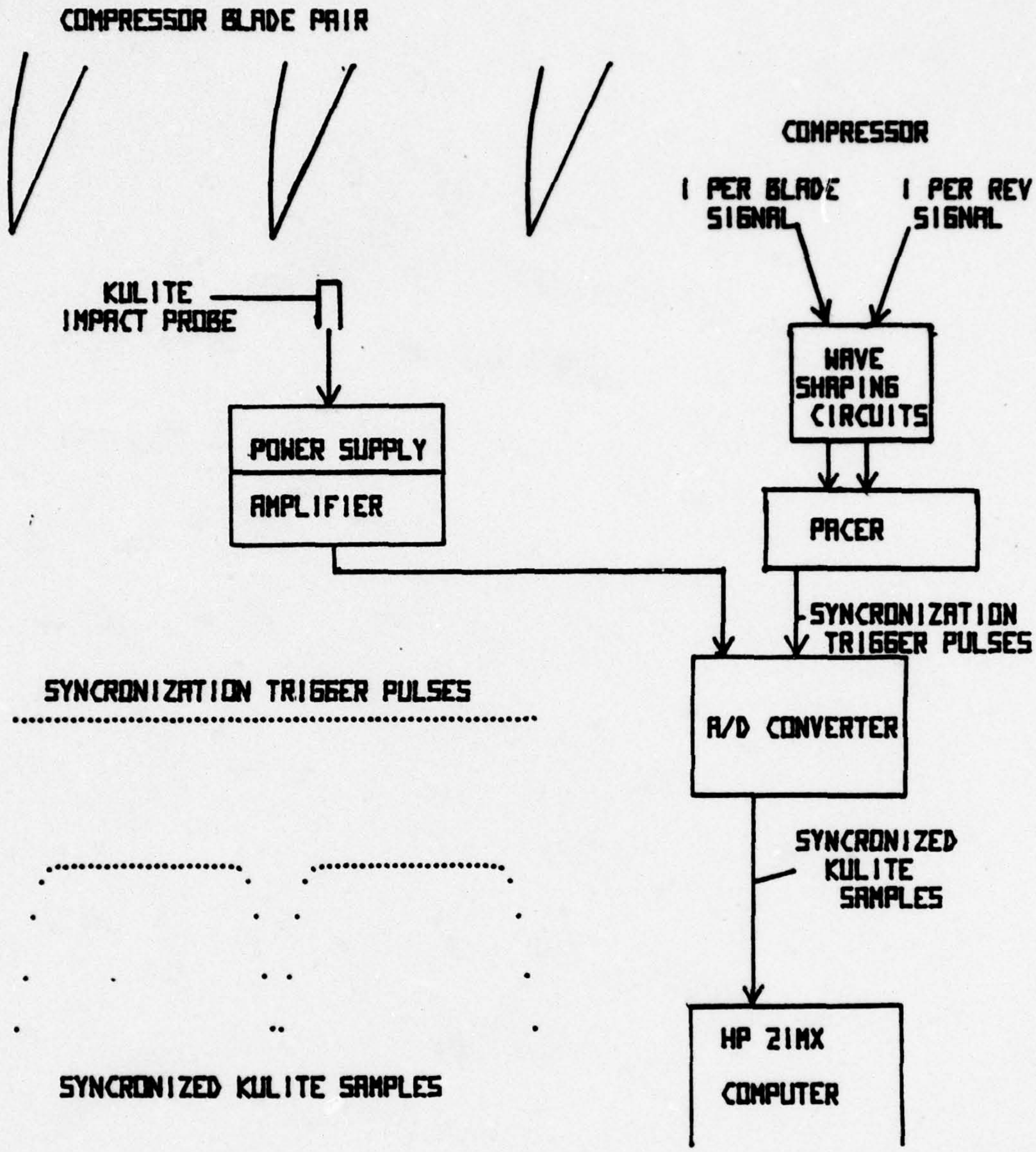


FIGURE 5. SYNCHRONIZED SAMPLING

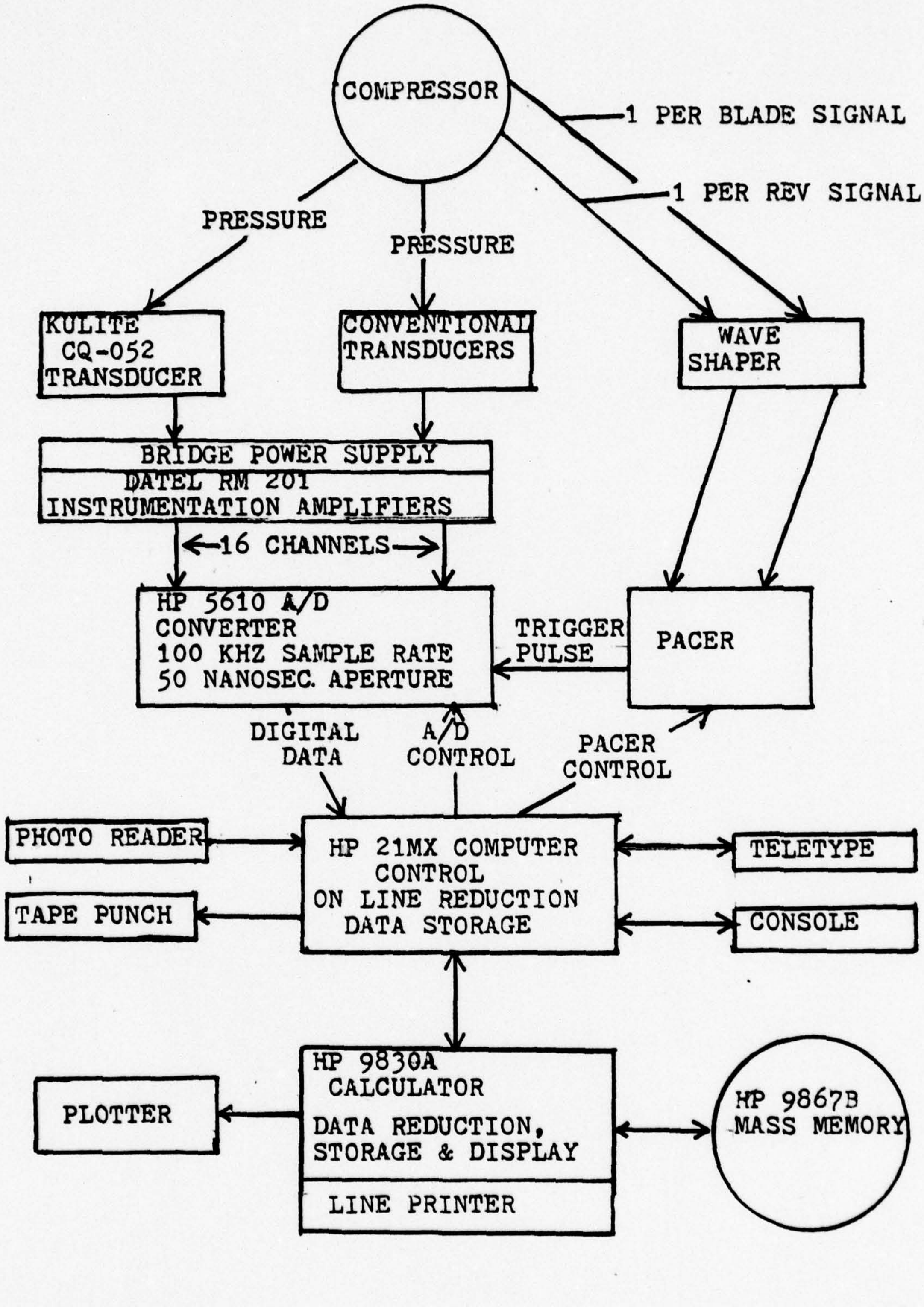


FIGURE 6. SCHEMATIC OF DATA ACQUISITION SYSTEM

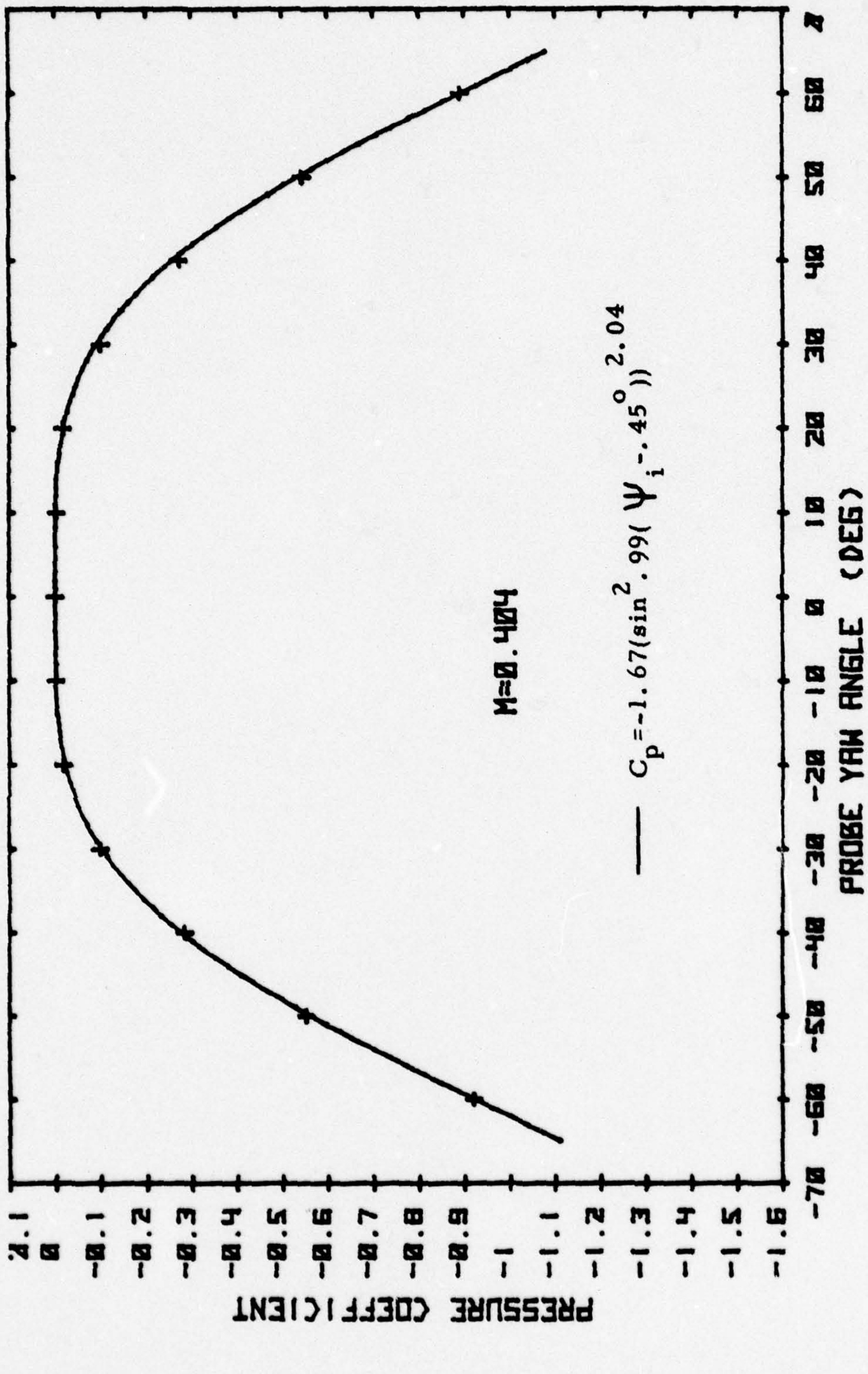


FIGURE 7a
CHARACTERISTICS OF THE KULITE-EQUIVALENT PNEUMATIC PROBE

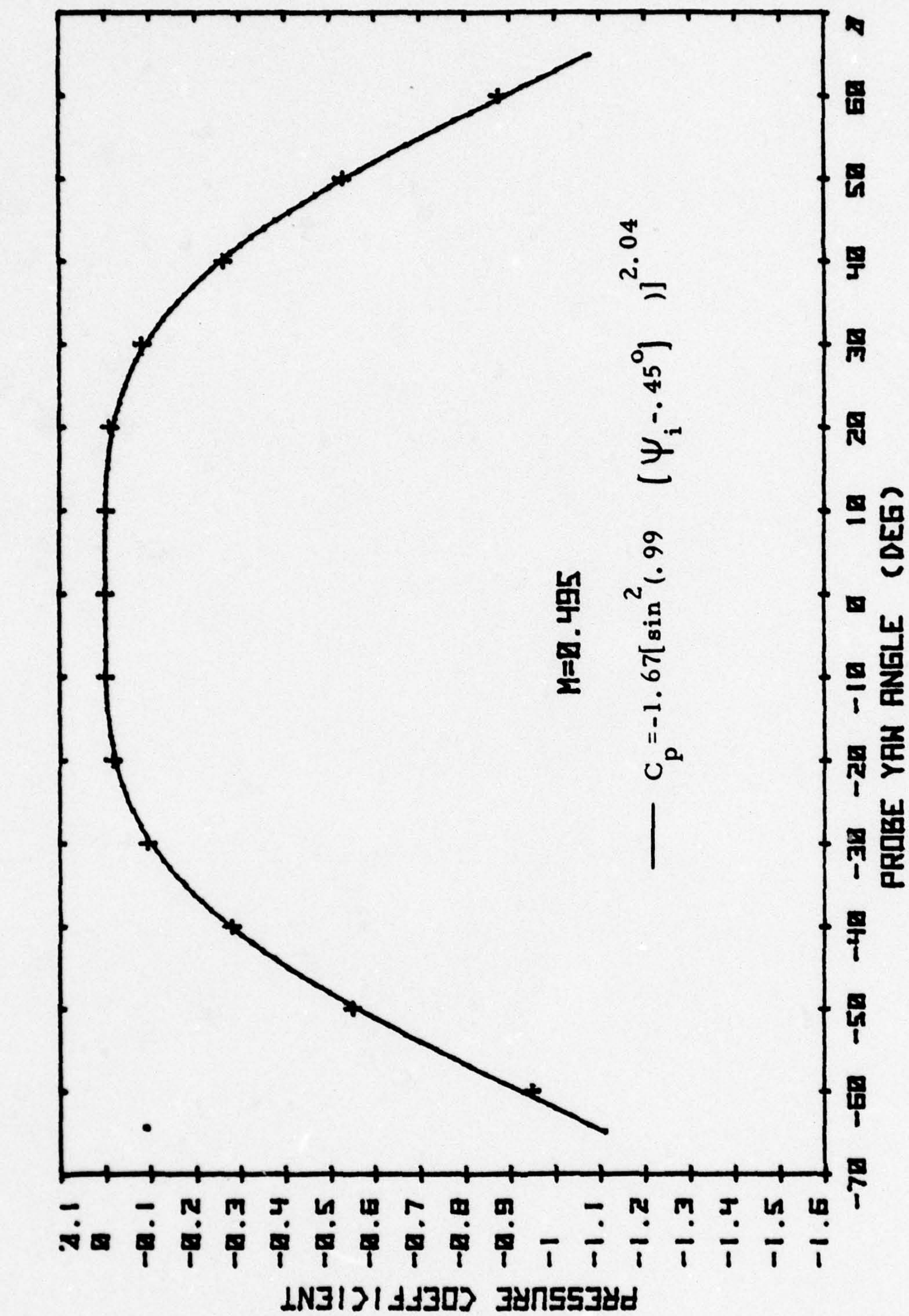


FIGURE 7b
CHARACTERISTICS OF THE KULITE-EQUIVALENT PNEUMATIC PROBE

Fig 7b

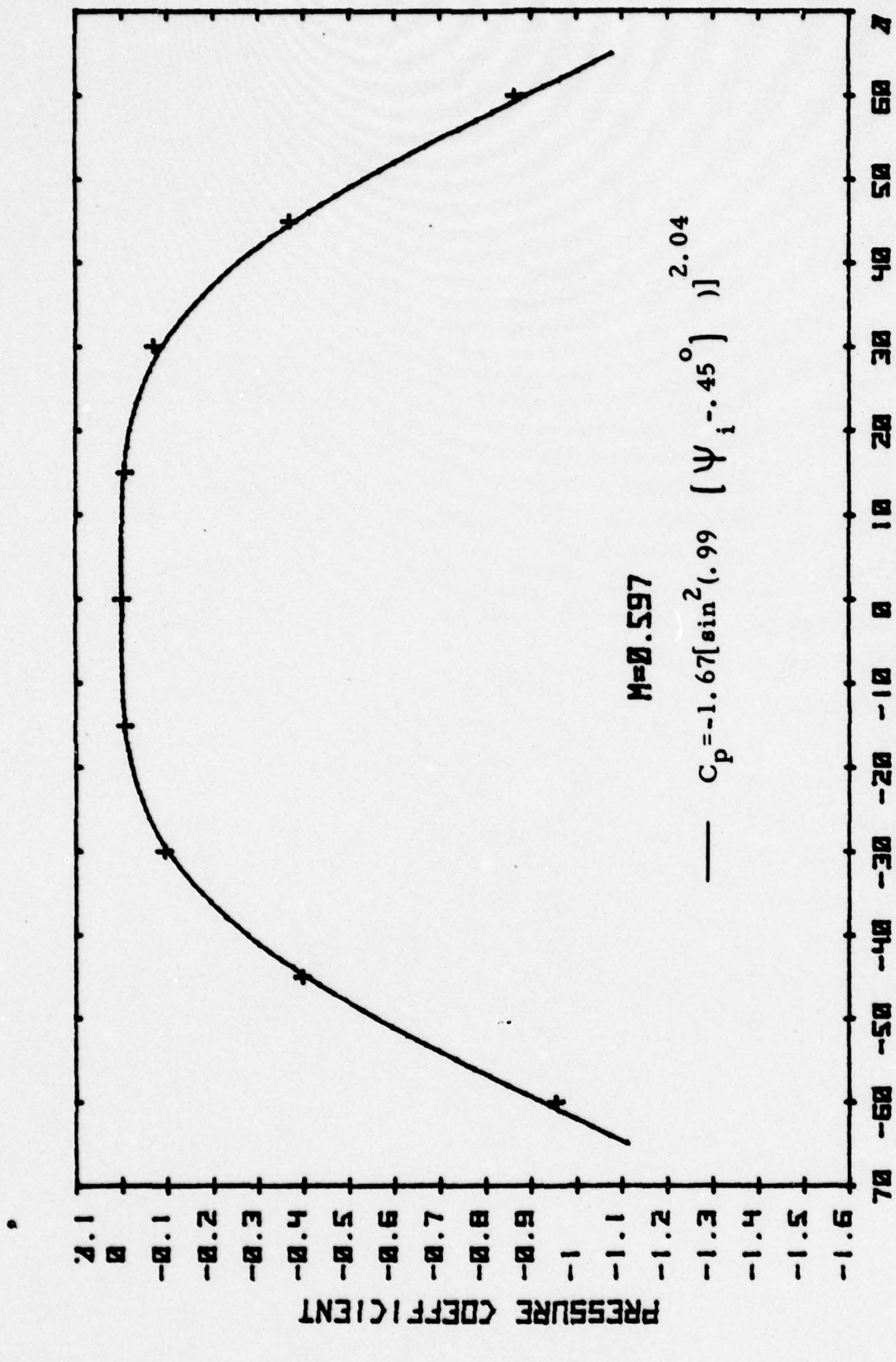


FIGURE 7c
CHARACTERISTICS OF THE KULITE-EQUIVALENT PNEUMATIC PROBE

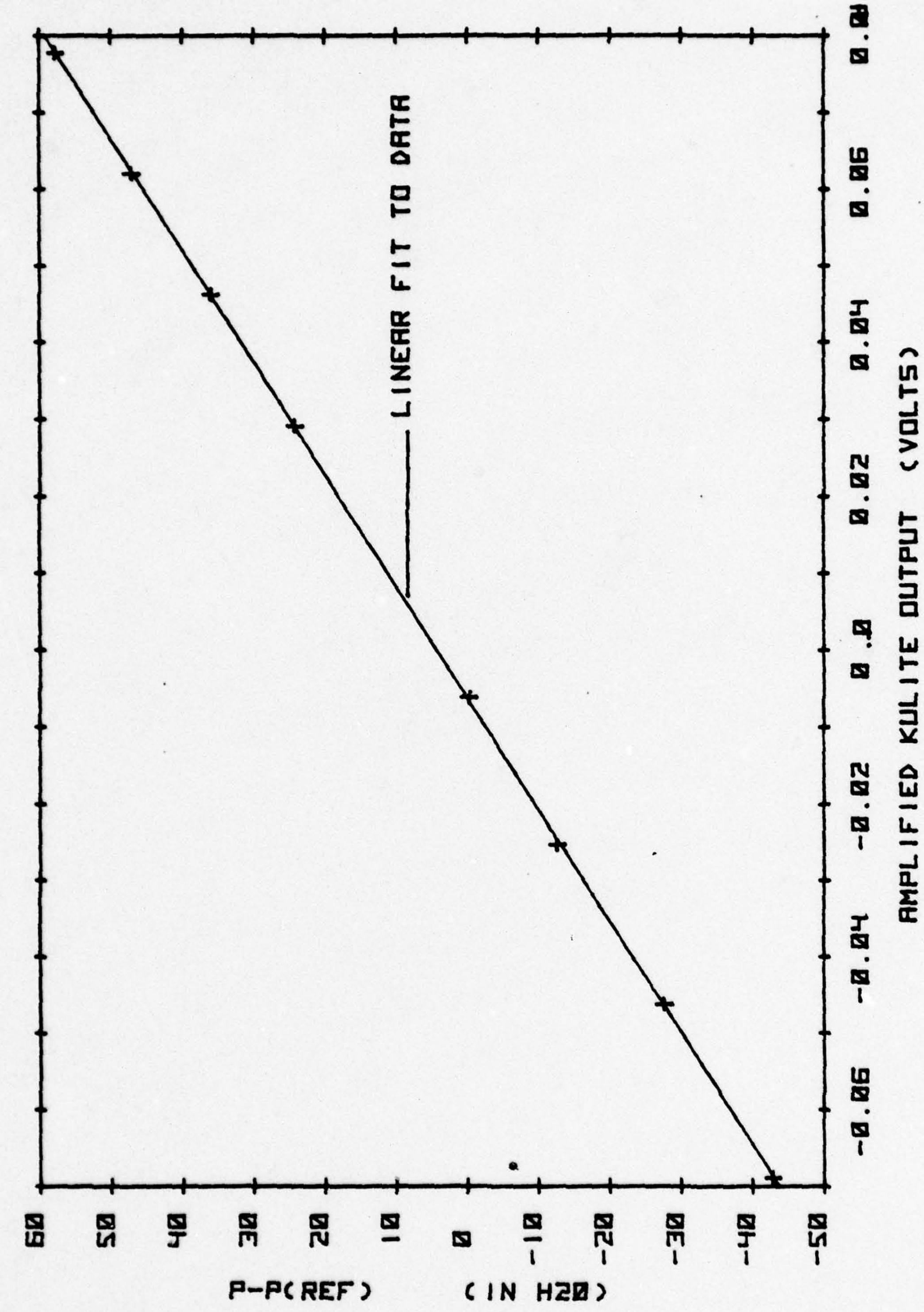


FIGURE 8. KULITE PROBE CALIBRATION CURVE

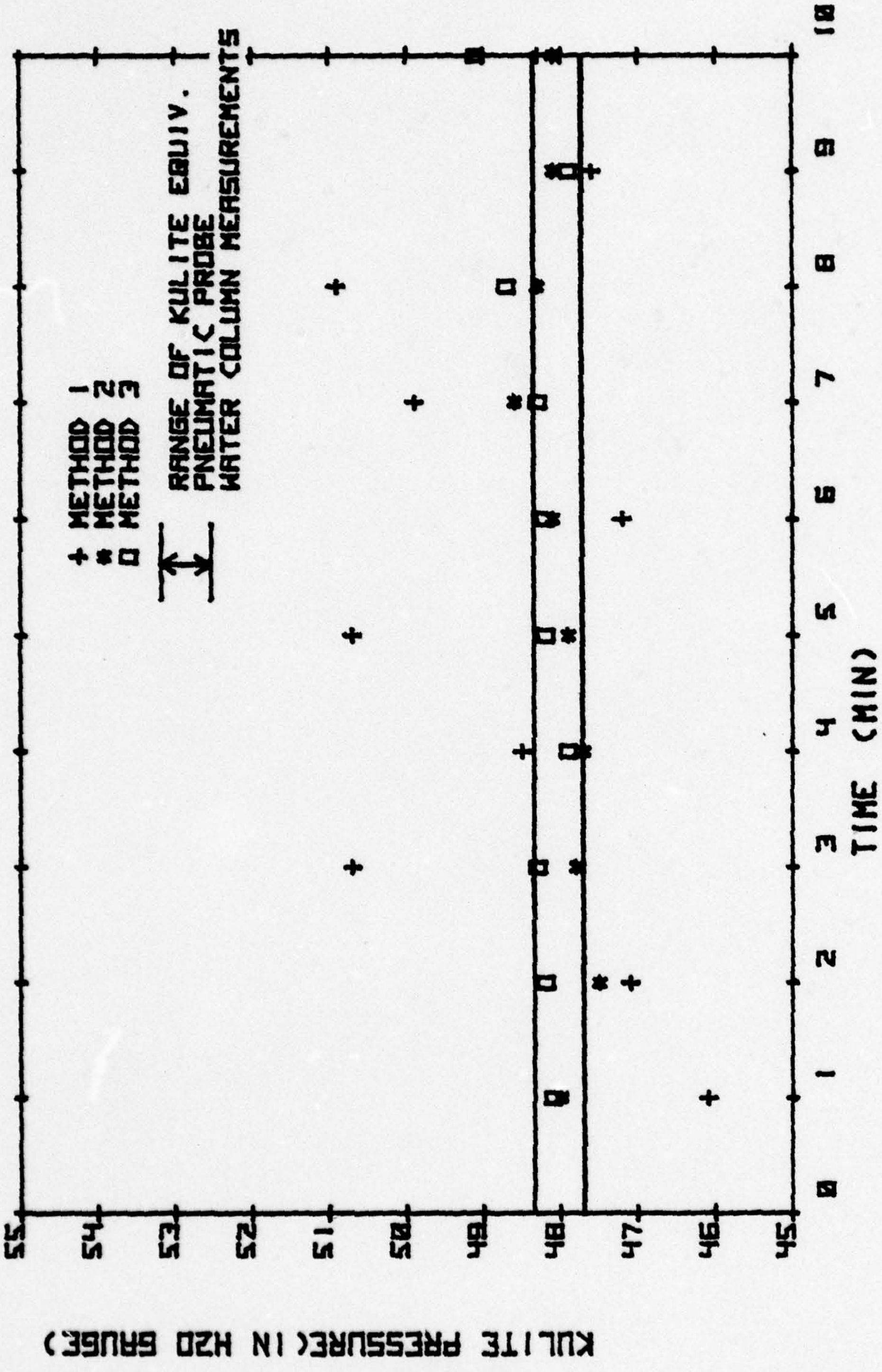


FIGURE 9
EVALUATION OF AVERAGING TECHNIQUES IN THE KULITE PROBE CALIBRATION TEST

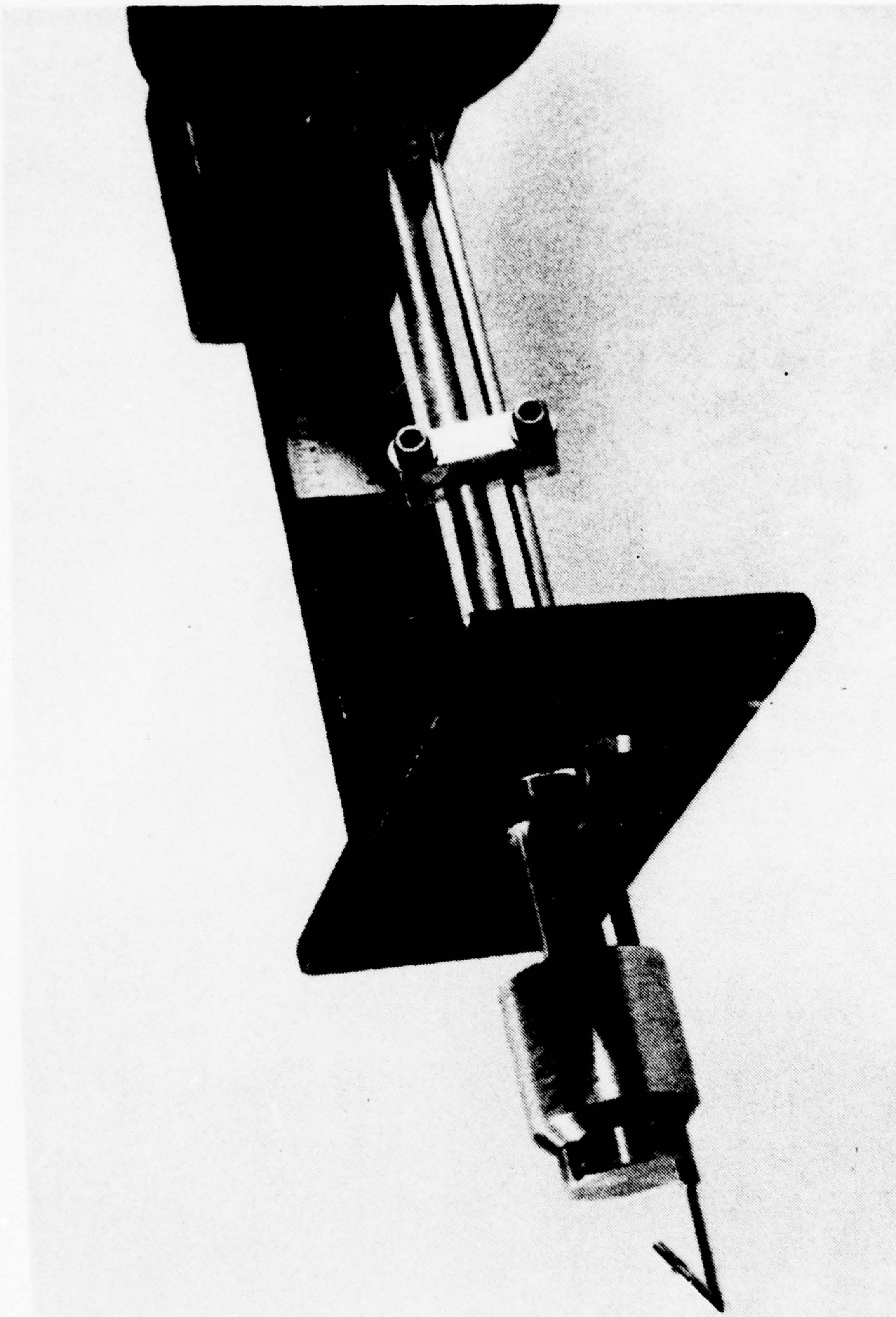


FIGURE 10
PHOTOGRAPH OF TYPE B PNEUMATIC EQUIVALENT PROBE
IN COMPRESSOR MOUNTING APPARATUS

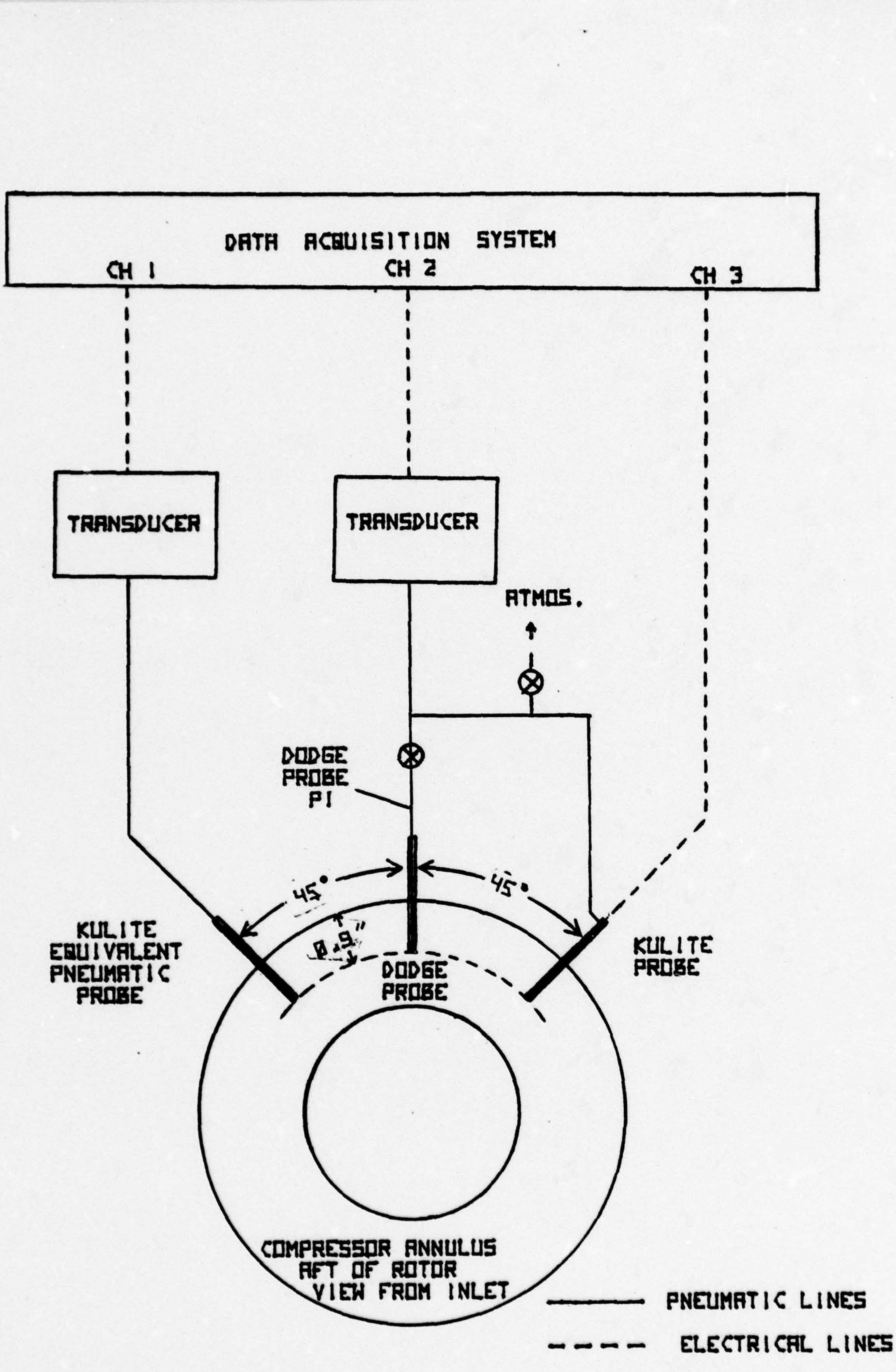


FIGURE 11. DIAGRAM OF COMPRESSOR TEST INSTALLATION

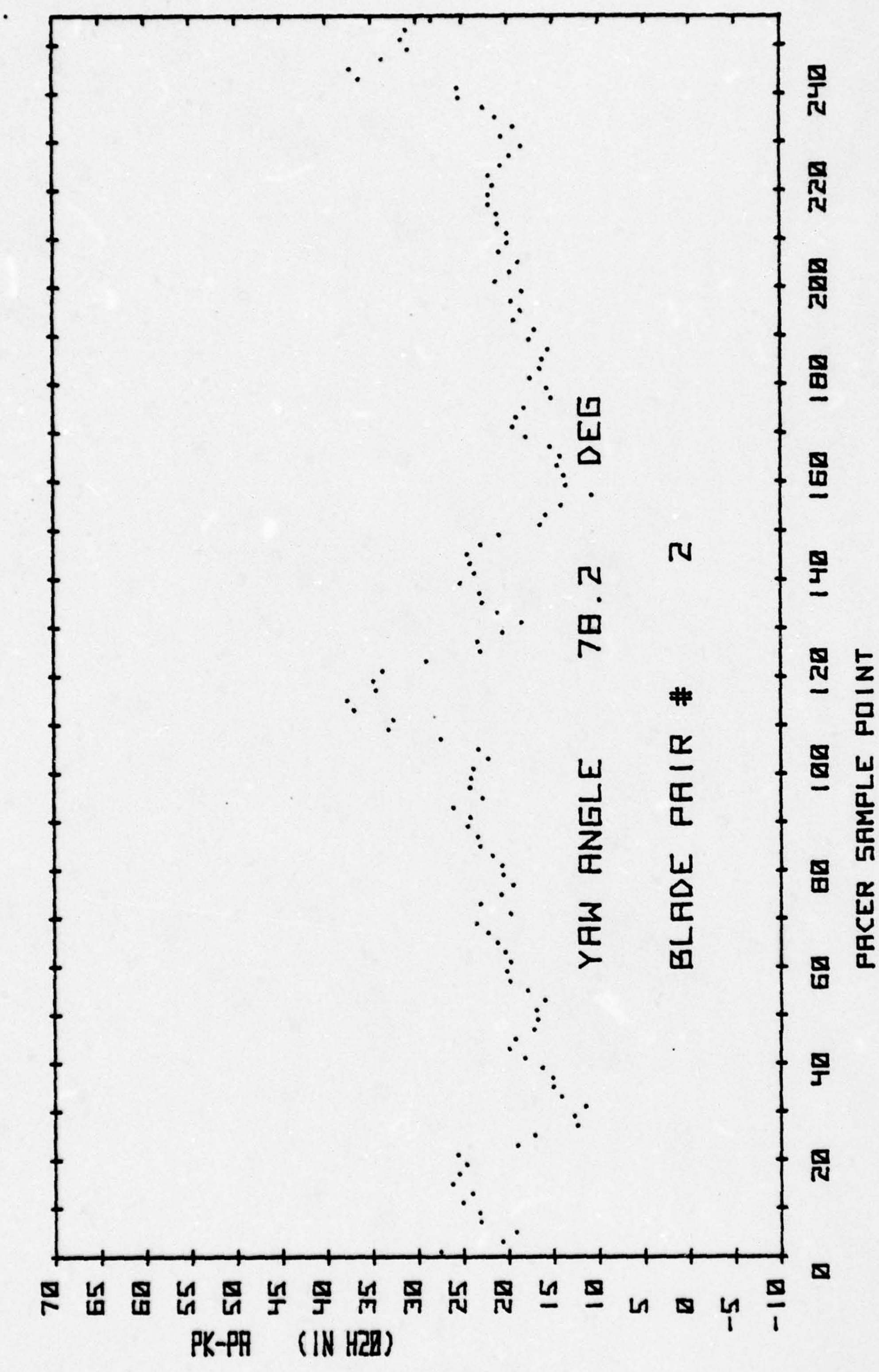


FIGURE 12a
BLADE PAIR 2 KULITE PRESSURES

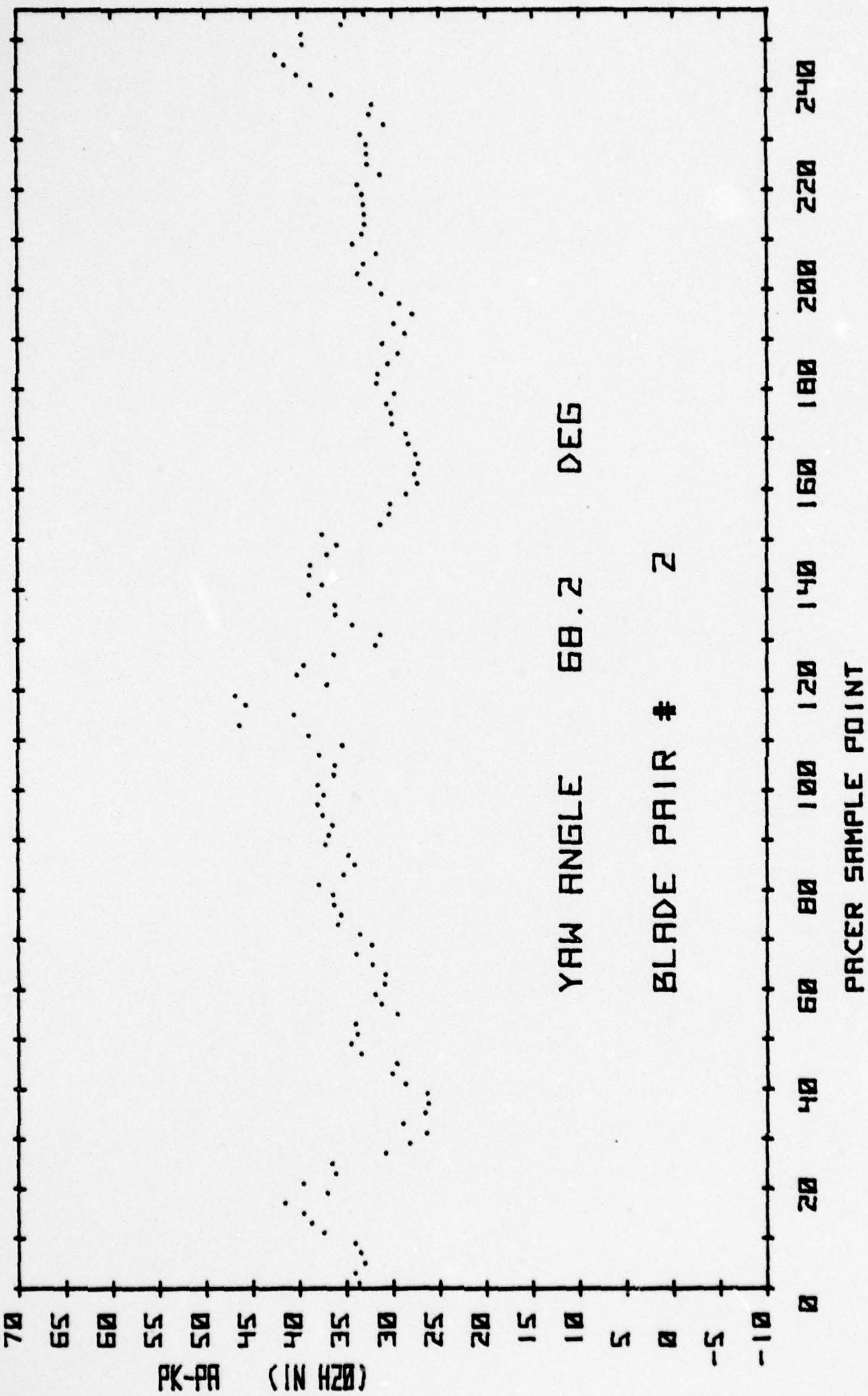


FIGURE 12b
BLADE PAIR 2 KULITE PRESSURES

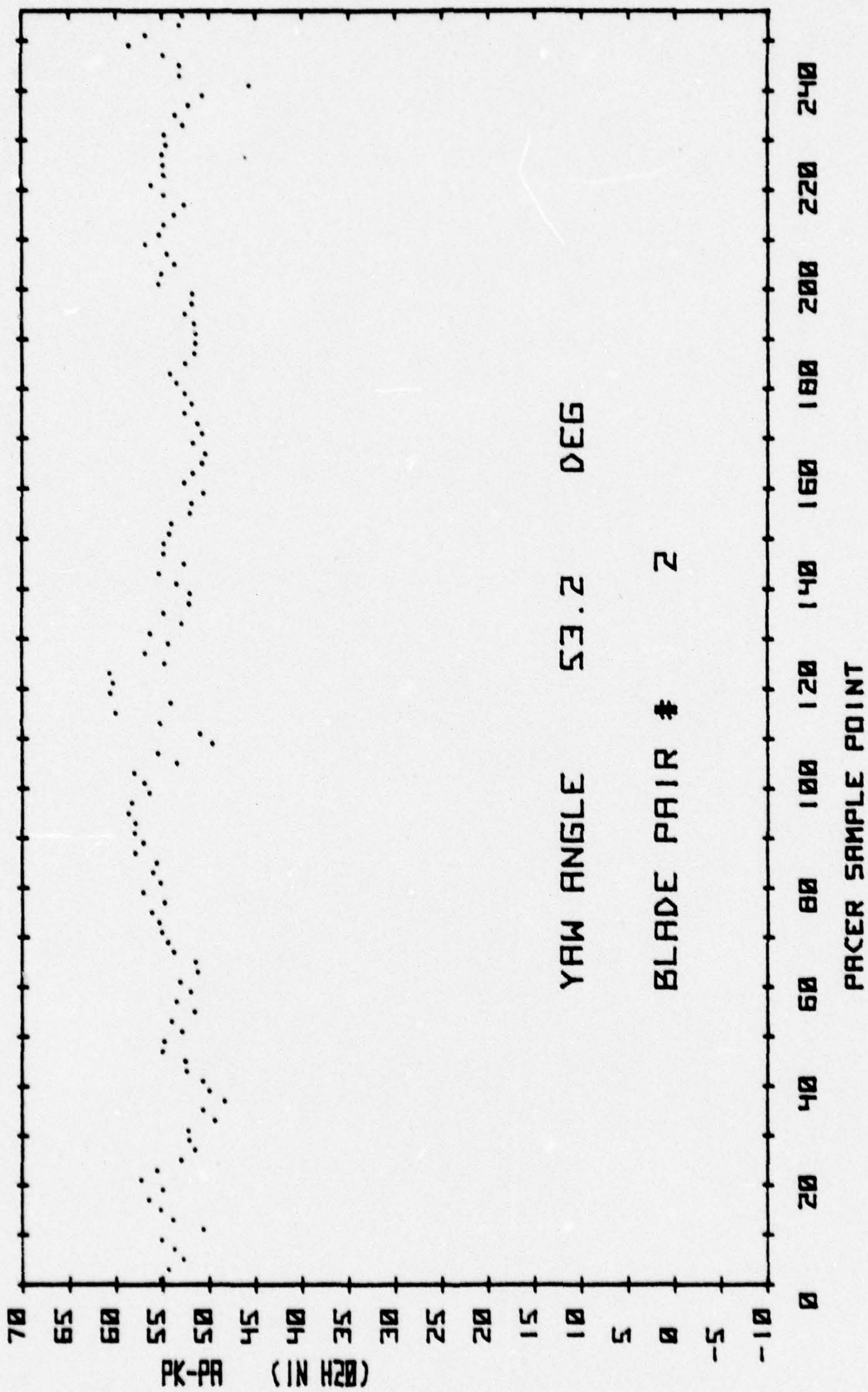


FIGURE 12c
BLADE PAIR 2 KULITE PRESSURES

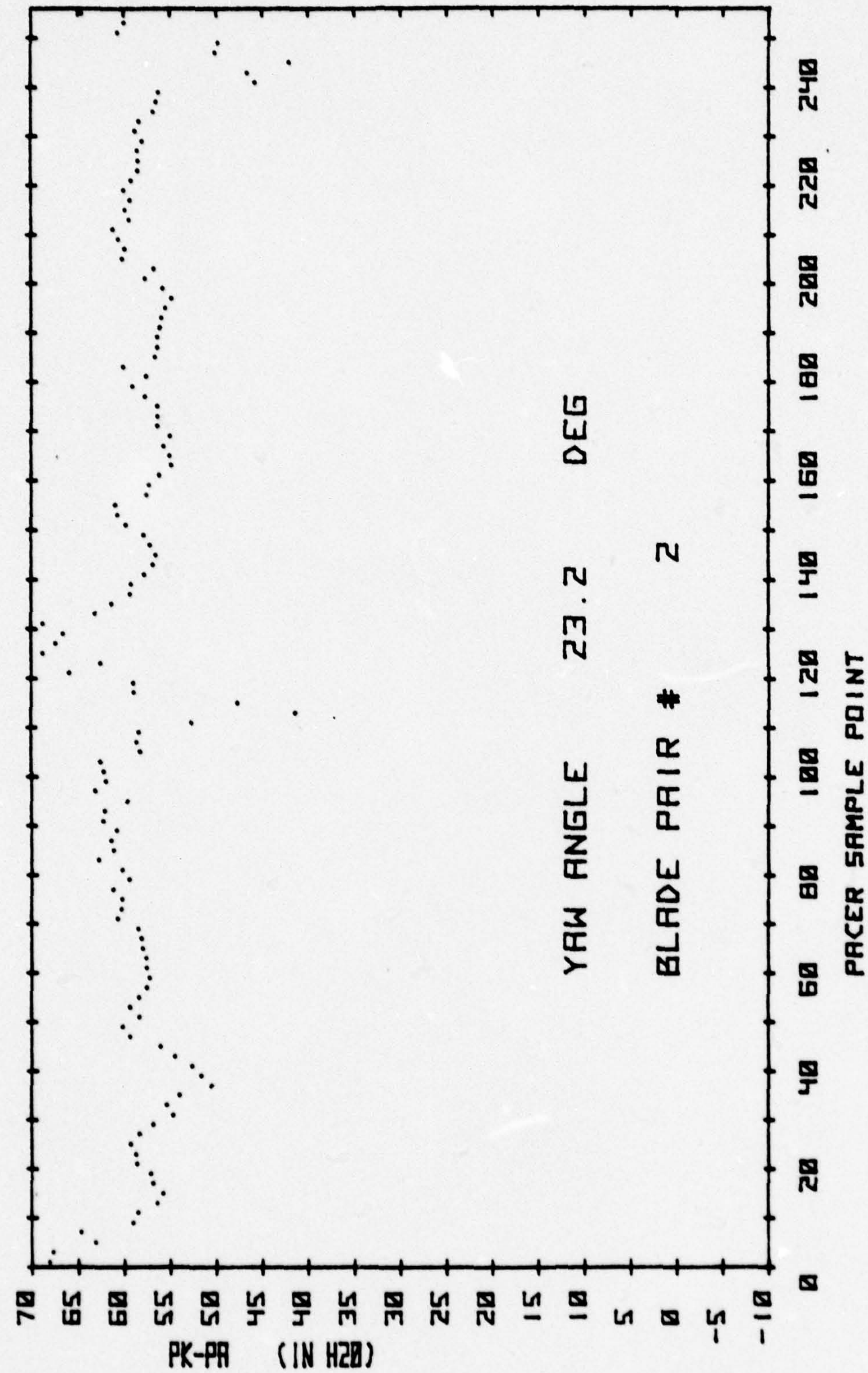


FIGURE 12d
BLADE PAIR 2 KULITE PRESSURES

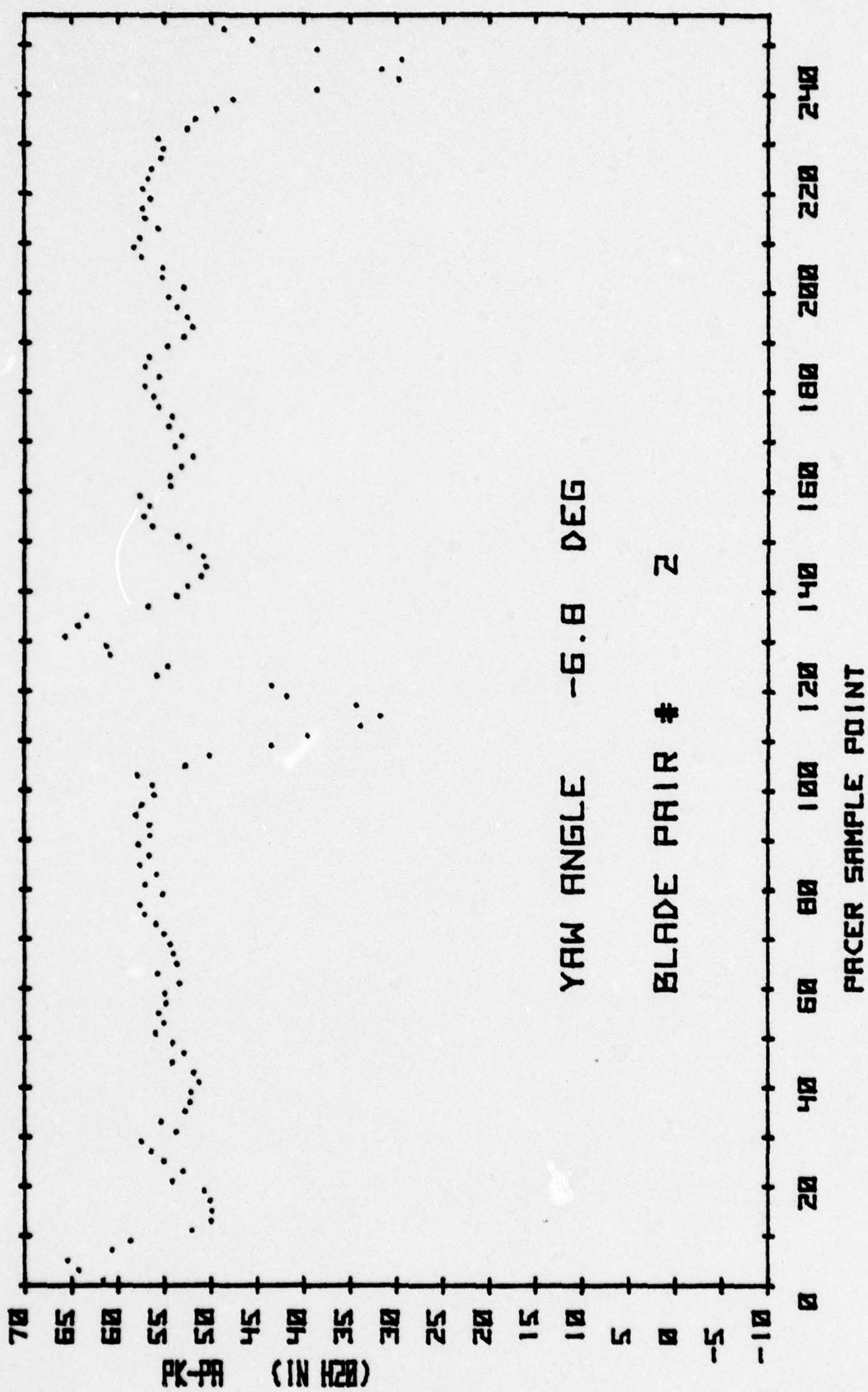


FIGURE 12e
BLADE PAIR 2 KULITE PRESSURES

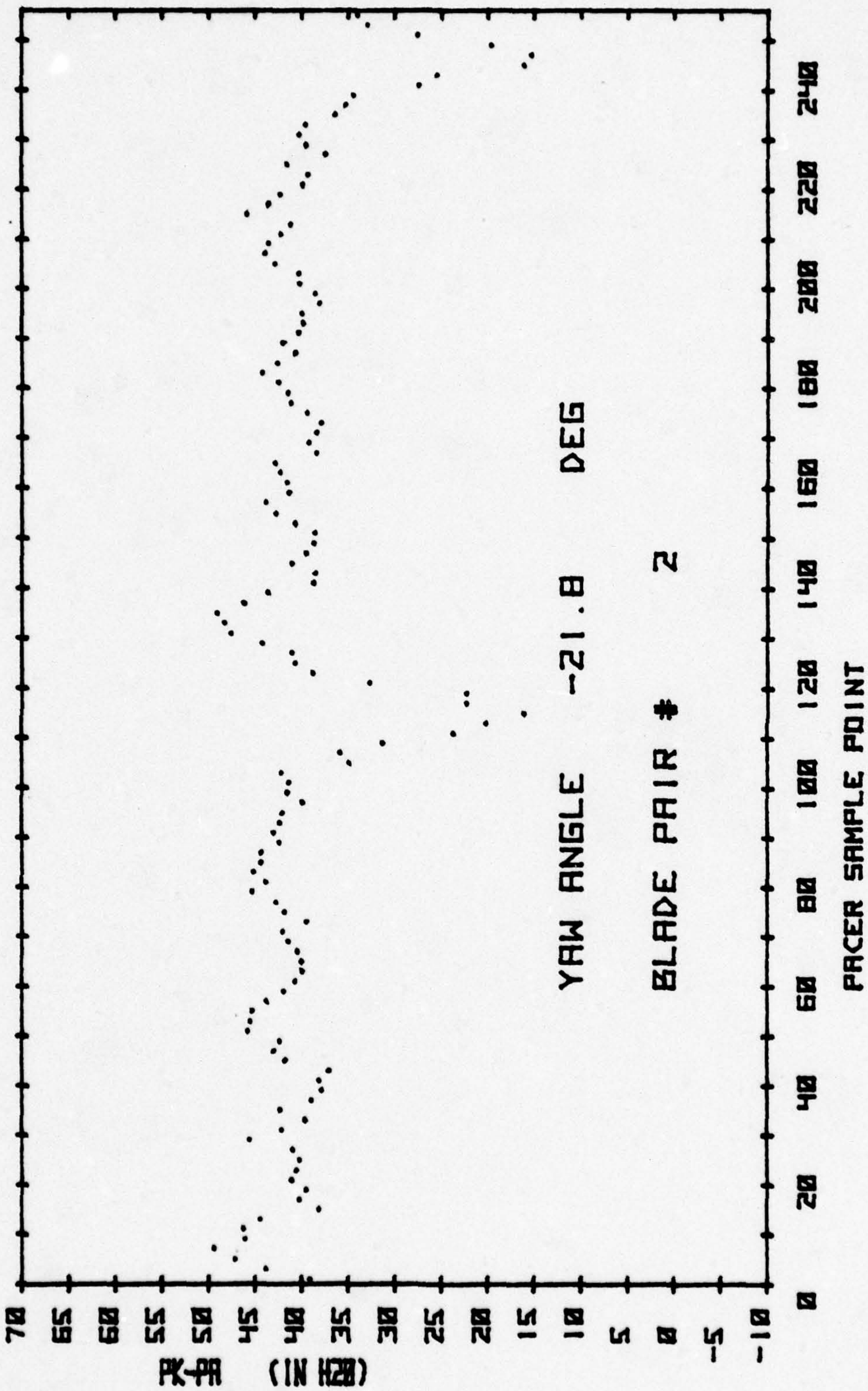


FIGURE 12f
BLADE PAIR 2 KULITE PRESSURES

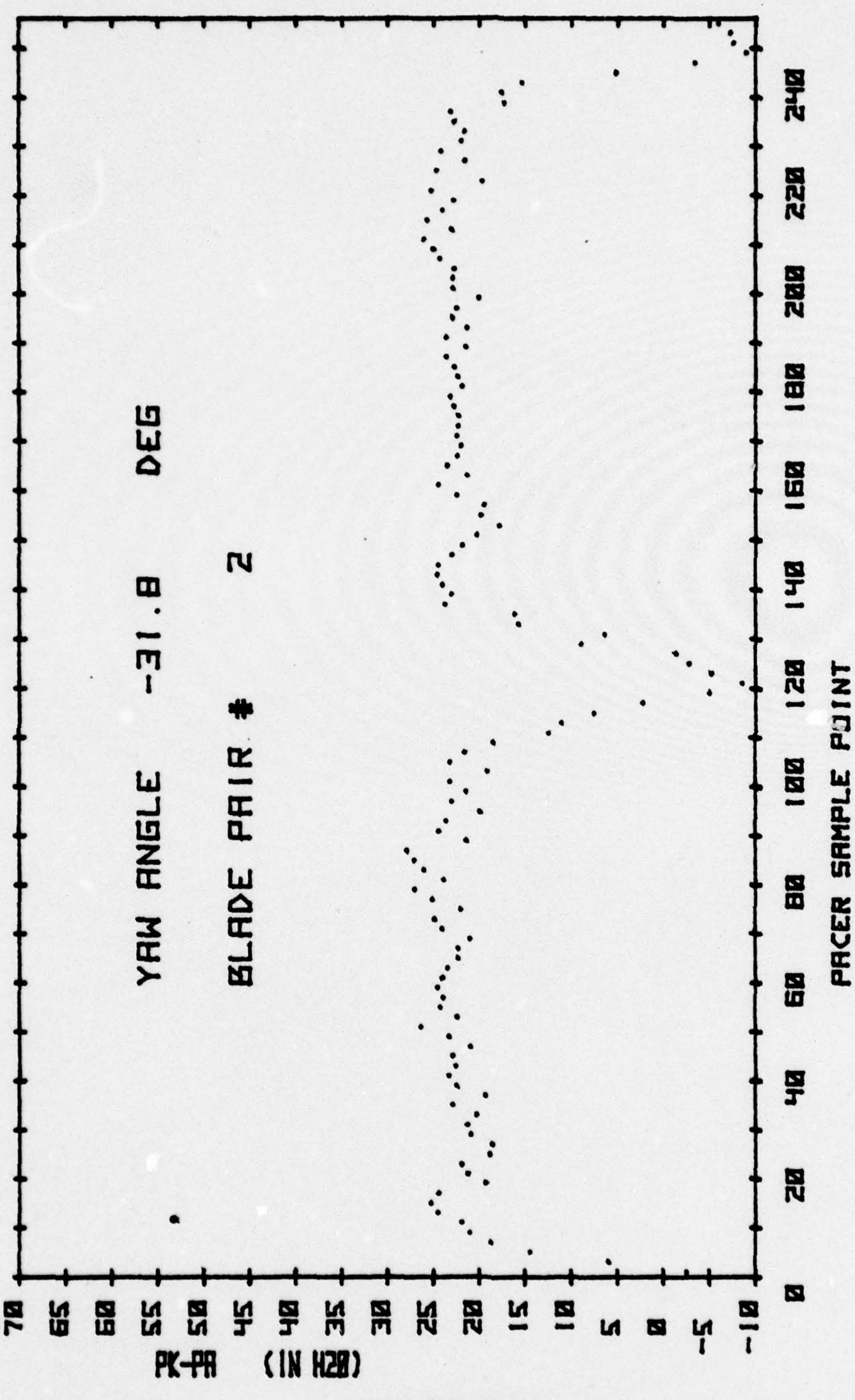


FIGURE 12g
BLADE PAIR 2 KULITE PRESSURES

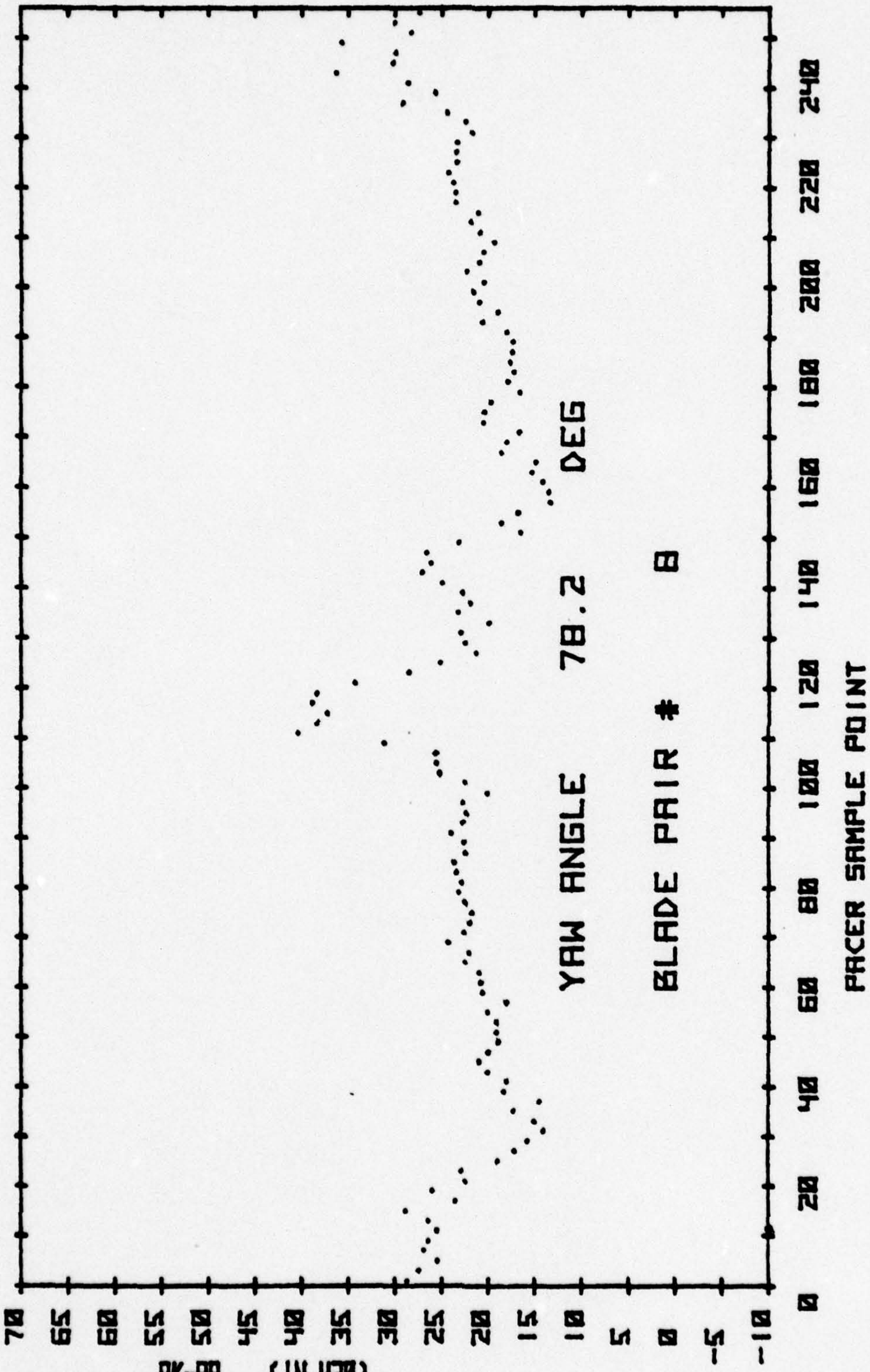


FIGURE 13a
BLADE PAIR 8 KULITE PRESSURES

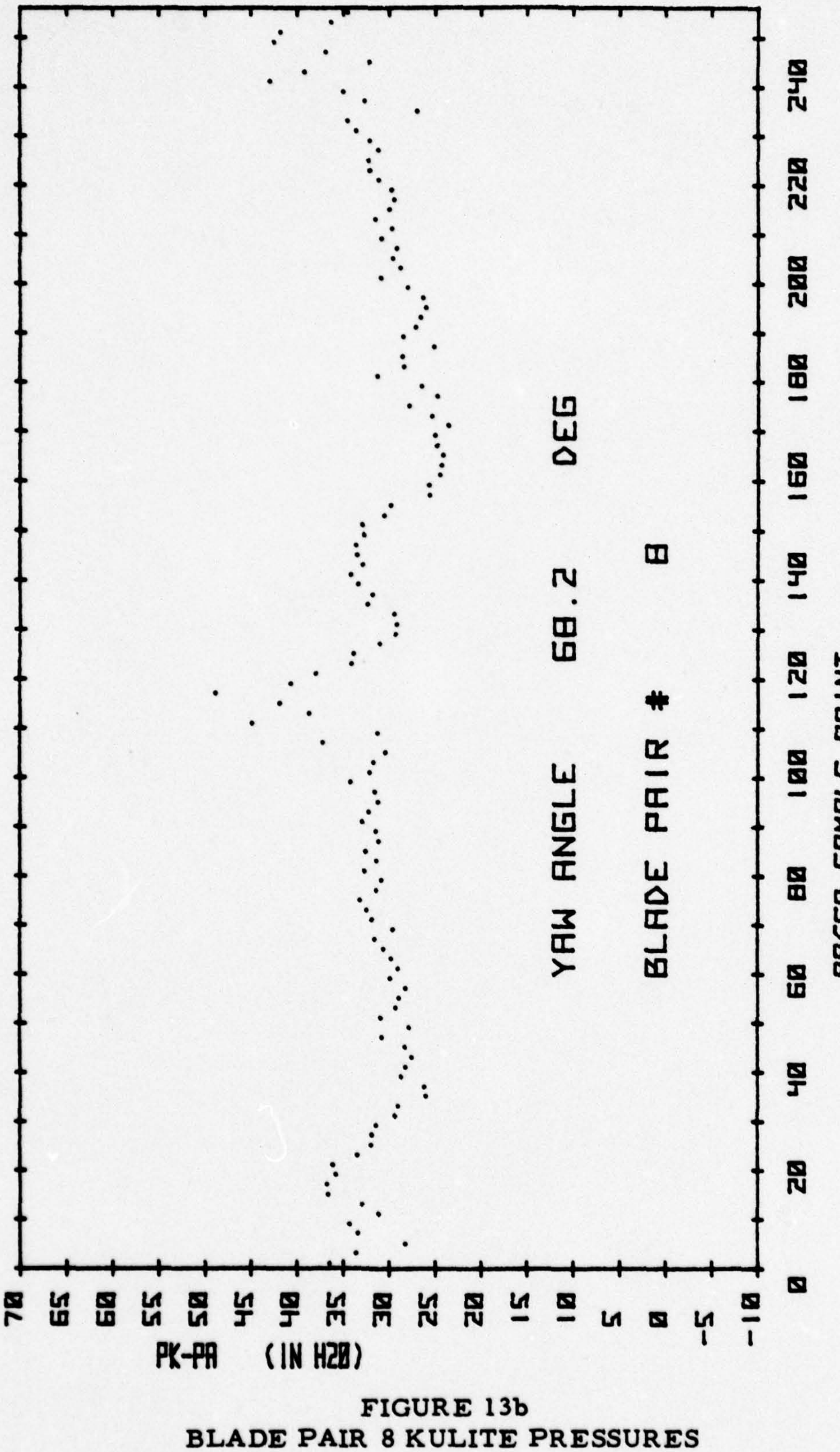


FIGURE 13b
BLADE PAIR 8 KULITE PRESSURES

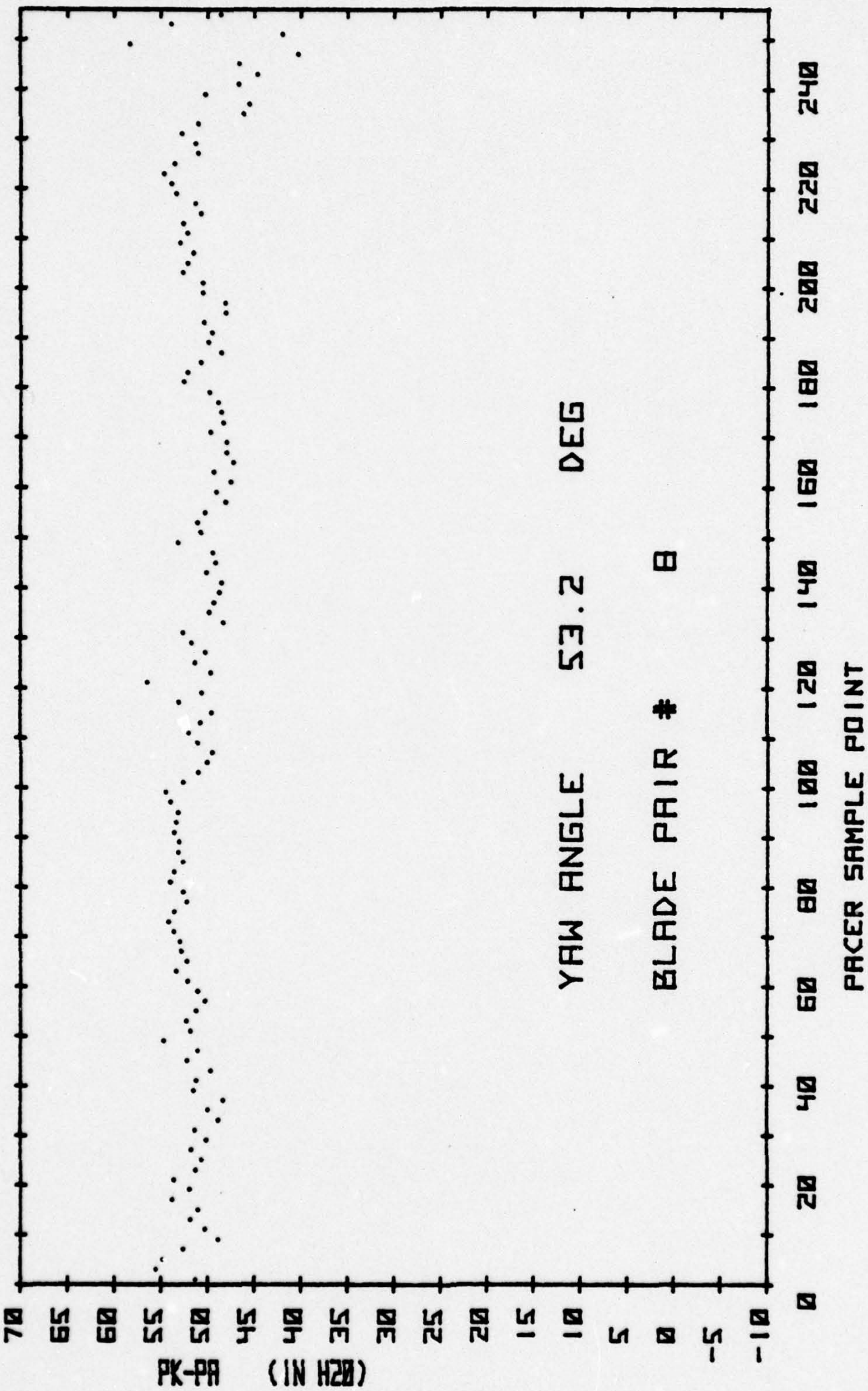


FIGURE 13c
BLADE PAIR 8 KULITE PRESSURES

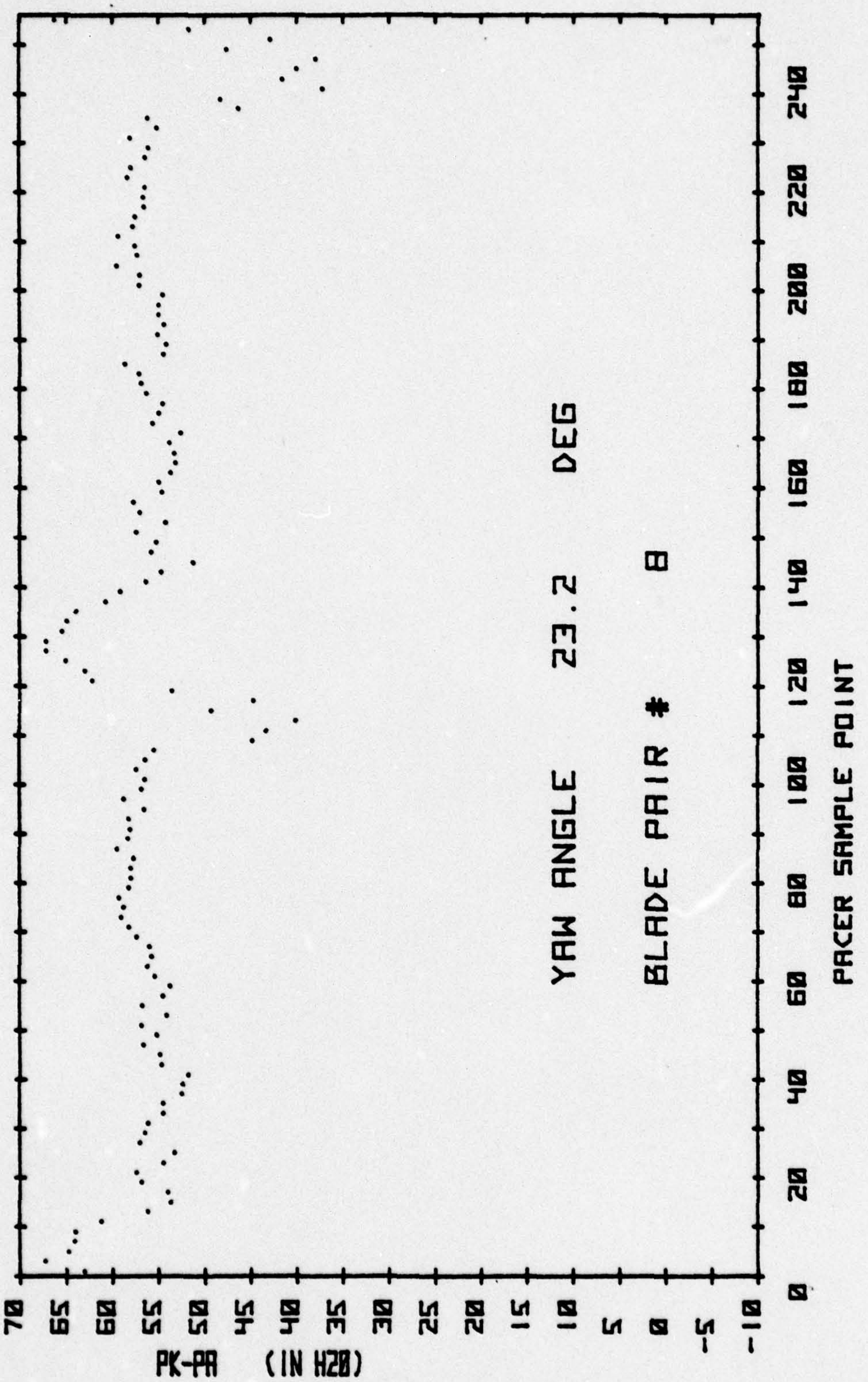


FIGURE 13d
BLADE PAIR 8 KULITE PRESSURES

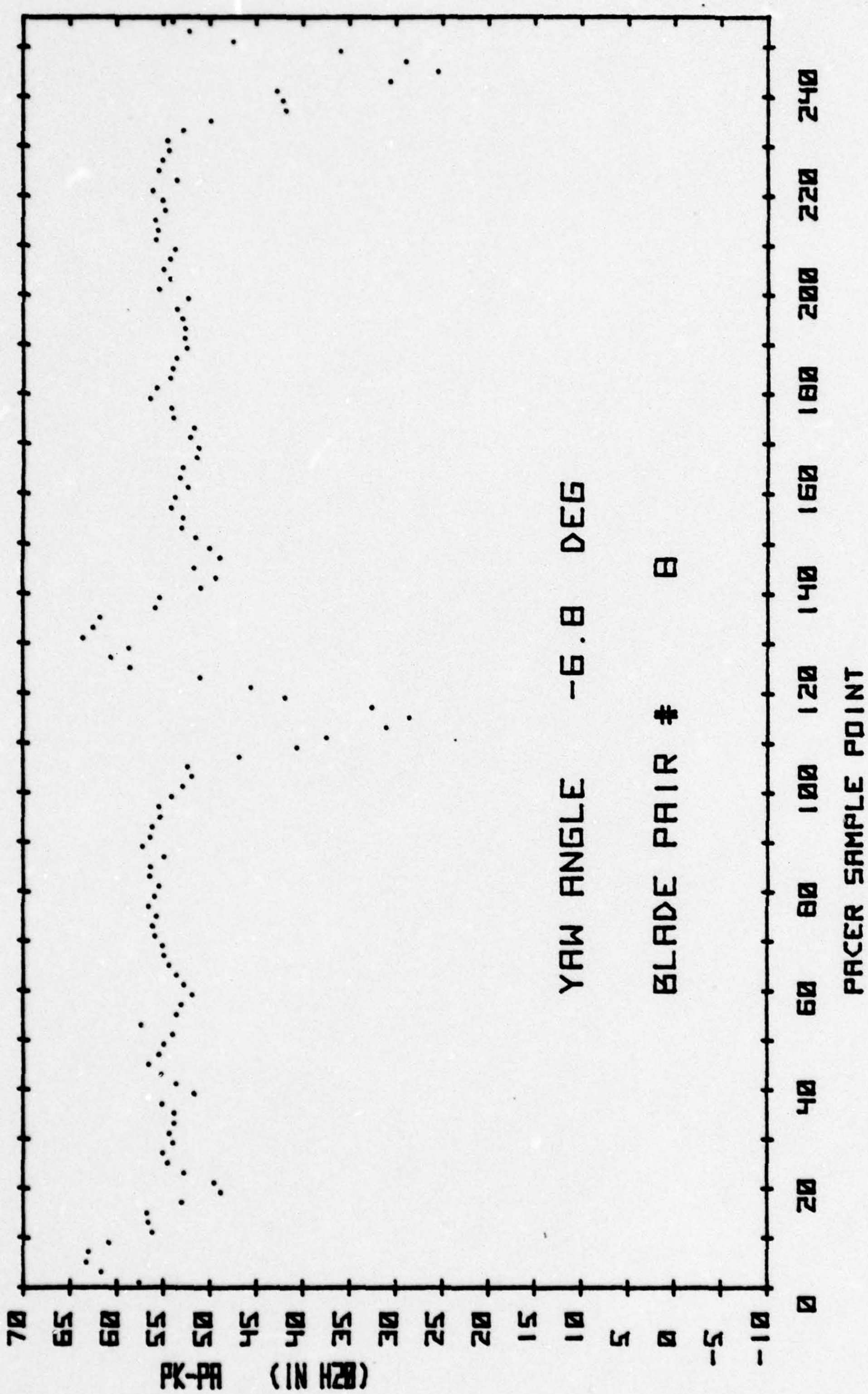


FIGURE 13e
BLADE PAIR 8 KULITE PRESSURES

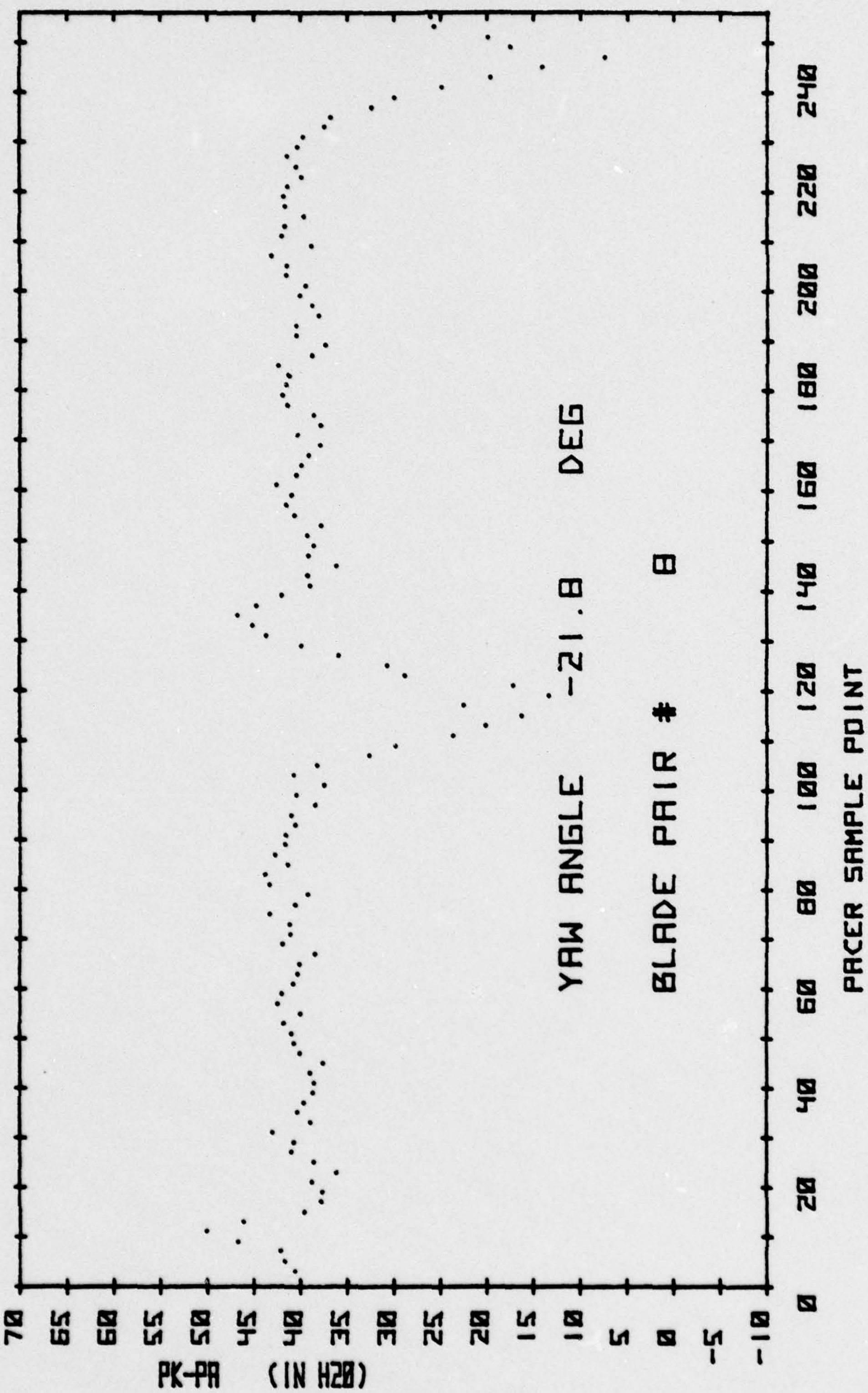


FIGURE 13f
BLADE PAIR 8 KULITE PRESSURES

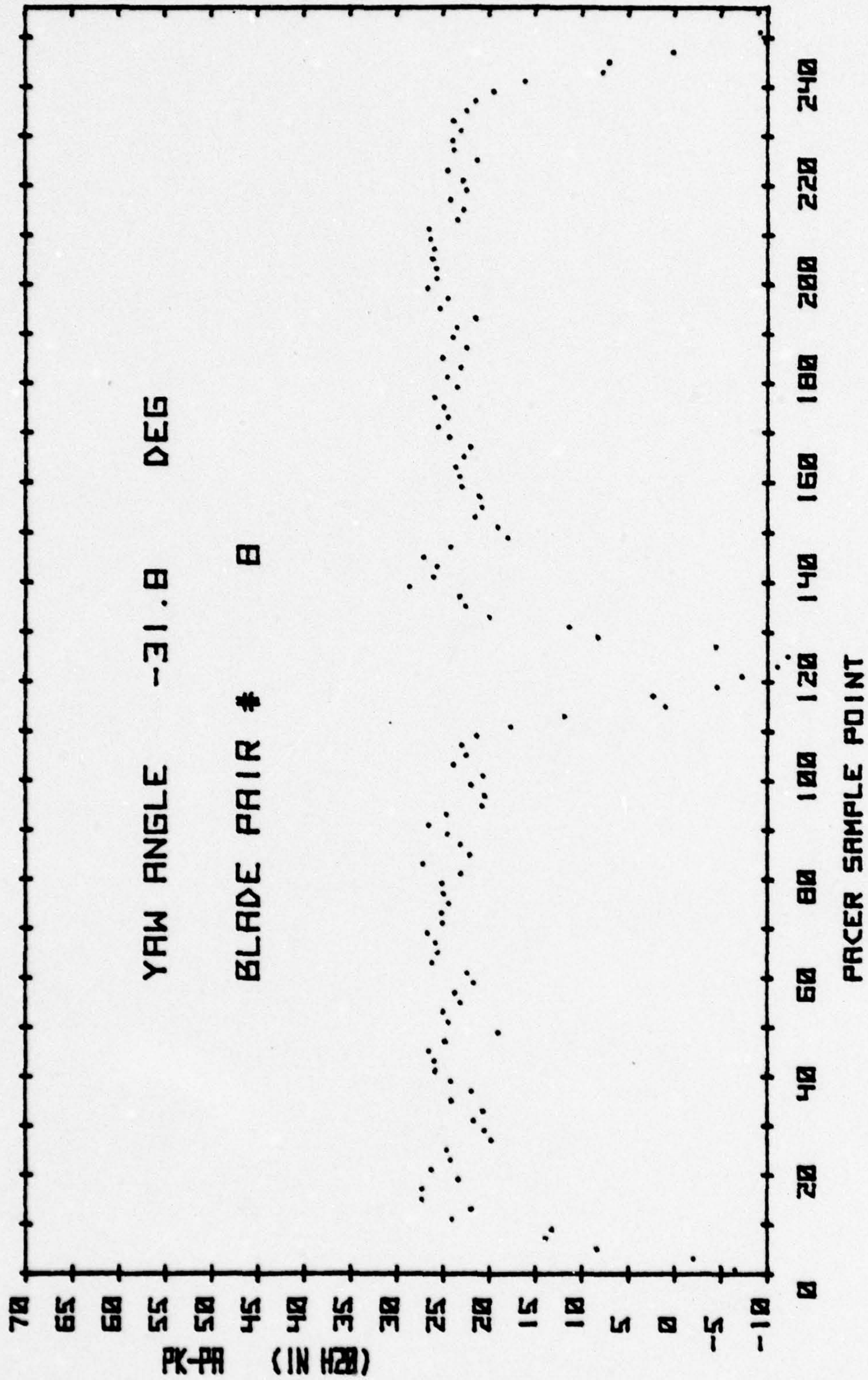


FIGURE 13g
BLADE PAIR 8 KULITE PRESSURES

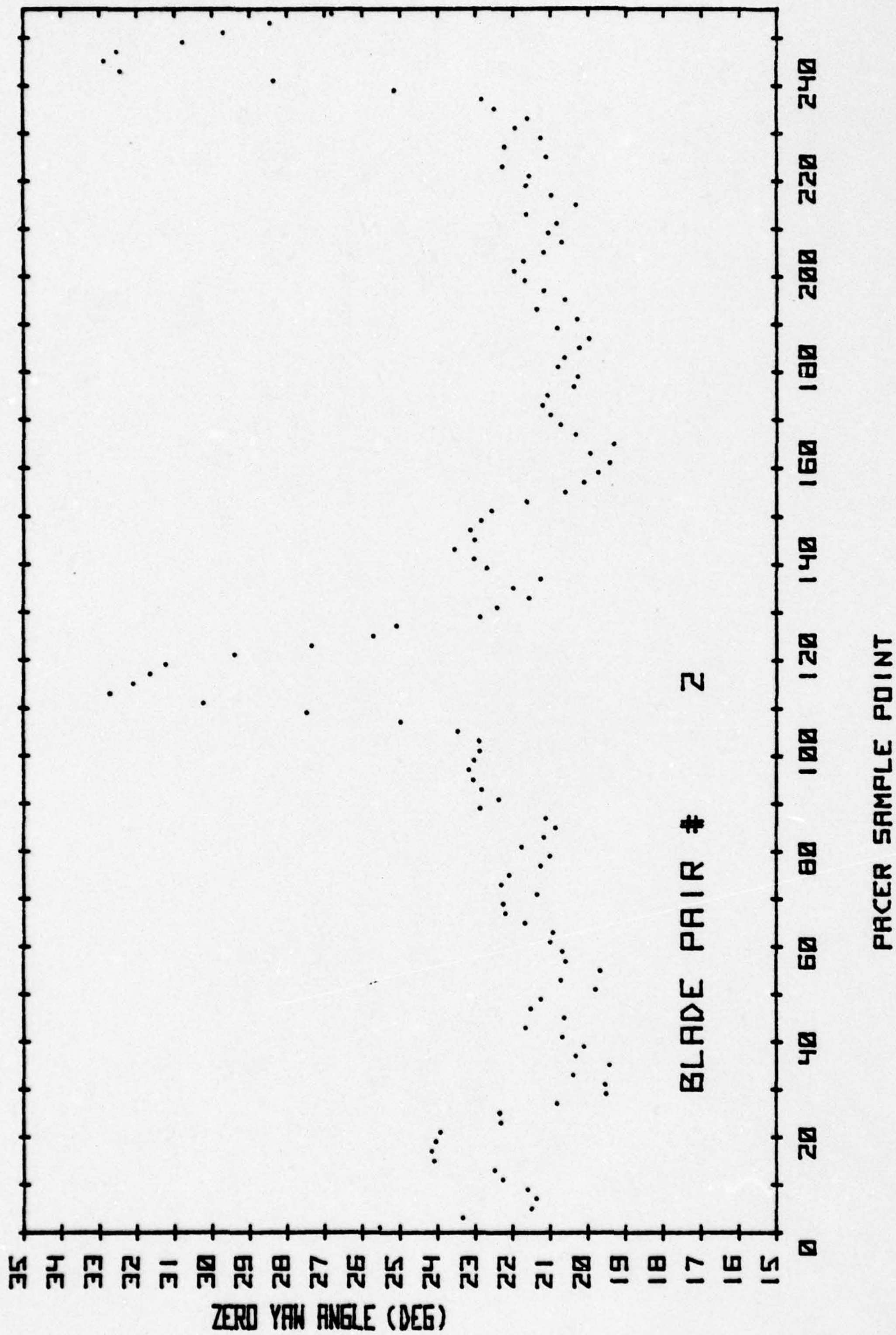


FIGURE 14. BLADE PAIR 2 ZERO YAW ANGLES

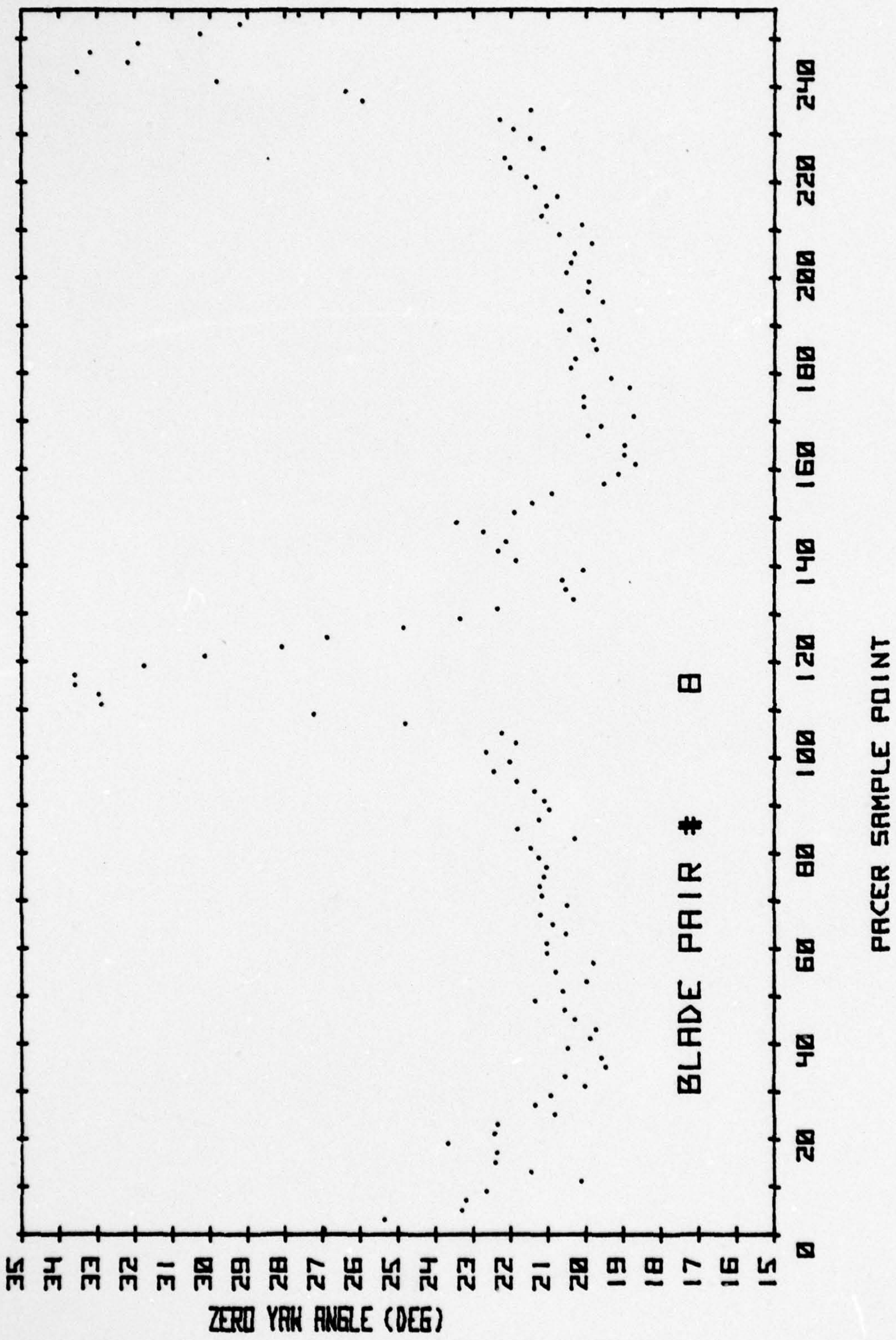


FIGURE 15. BLADE PAIR 8 ZERO YAW ANGLES

APPENDIX A

DETERMINATION OF THE CHARACTERISTICS OF CYLINDRICAL IMPACT PROBES

A.1 Calibration Tests

A cylindrical impact probe was constructed to have a tip with the same dimensions as the individual sensors in the Dodge probe. The probe is shown in Figure A1. Calibration tests of the probe were conducted in a seven inch free air jet at five Mach numbers varying from 0.2 to 0.5, yaw angles from -90° to 90° and pitch angles from -40° to 40°. Both yaw and pitch angle were varied at Mach numbers 0.2 and 0.5. Yaw angle alone was varied at Mach numbers 0.3, 0.35, and 0.4. A description of the free jet apparatus is given in Appendix B of Ref. 1. A Prandtl probe was used to measure the total pressure at the same radial station as the test probe. A conventional strain gauge transducer and scanivalve were used to read the pressures from the Prandtl probe, the probe under calibration and the atmospheric reference. Frequent cross checks to a water column manometer were made to insure accuracy. An example of the results is shown in Fig. A2, where the pressures measured in yaw surveys at five Mach numbers are plotted.

A.2 Analysis of Results

The probe pressure, P_p, at each yaw and pitch angle was reduced to a nondimensional pressure coefficient $\overline{Cp}$ defined as

$$\overline{Cp} = \frac{P_p - P_t}{\gamma/_2 Ps\ M^2} \tag{A1}$$

where P_t = reference impact pressure from the Prandtl probe, P_s = static pressure (atmospheric), M = Mach number calculated using reference impact pressure and atmospheric static pressure, and $\gamma = 1.4$ = ratio of specific heats. The values obtained for Cp were plotted against the angle of the flow to the probe axis, Ψ. The results are shown in Fig. A3. For angles that were a combination of pitch and yaw angle, the flow angle relative to the probe axis was calculated using the geometrical relationship.

$$\Psi = \cos^{-1} \quad (\cos\alpha \cos \emptyset) \tag{A2}$$

where α is the yaw angle and $\emptyset$ is the pitch angle of the flow to the cylindrical axis of the probe. Table A1 shows the combinations of pitch and yaw angles from which the angles in Figures A3g and A3i were computed.

The expression chosen to represent the data at each Mach number was $\overline{Cp} = \overline{A}(\sin^2 B(\Psi - \Psi_o))^N$. At least squares algorythm was developed for the computer which determined the constant coefficients $\overline{A}$, B, Ψ_o and N from given data. The algorithm is described in Appendix B. Further examination revealed that for this probe the Mach number dependence could be accounted for by redefining $A = A * M^{.01}$, so that from Equation A1, the expression

$$Cp = A\,(\sin^2 B\,(\Psi - \Psi_o))^N \qquad \text{(A3)}$$

where Cp was defined as

$$Cp = \frac{P_p - P_t}{\gamma/2 P_s M^2 .01} \qquad \text{(A4)}$$

and A, B, Ψ_o and N were constants, described the behavior at all Mach numbers tested. This expression was found to hold well as long as the yawed probe pressure did not fall below the static pressure, which occurred at a flow angle of approximately $\pm 60^\circ$. Application of this expression (Equation A3) in a method for representing the calibration of the Dodge probe is described in Appendix D. The expression was used in the present work to determine the yaw angle from measurements made with a cylindrical impact probe set at different angles to the flow. This application is discussed in Appendix B.

In the pitch angle surveys of the pneumatic probe shown in Fig. A-1 there was a noticeable assymetry in the distributions thought to be an effect caused by the probe stem. The assymetry should be noted in the application of the third method of calibration for multiple sensor probes described in Appendix D.

Angle settings for Fig A-3g

Yaw Angle	Pitch Angle	Flow Angle
-60	30	-64.34
-50	25	-54.37
-40	20	-43.96
-30	15	-33.23
-20	10	-22.27
-10	5	-11.17
0	0	0
10	5	11.17
20	10	22.27
30	15	33.23
40	20	43.96
50	25	54.37
60	30	64.34

Angle settings for Fig A-3i

Yaw Angle	Pitch Angle	Flow Angle
15	-40	-42.27
15	-35	-37.70
15	-30	-33.22
-5	-25	-28.90
15	-20	-24.81
15	-15	-21.09
15	-10	-17.96
15	- 5	-15.79
15	0	15
15	5	15.79
15	10	17.96
15	15	21.09
15	20	24.81
15	25	28.90
15	30	33.22
15	35	37.70
15	40	42.27

TABLE A-1 ANGLE SETTINGS USED TO COMPUTE FLOW ANGLES IN FIGURES A-3g AND A-3i

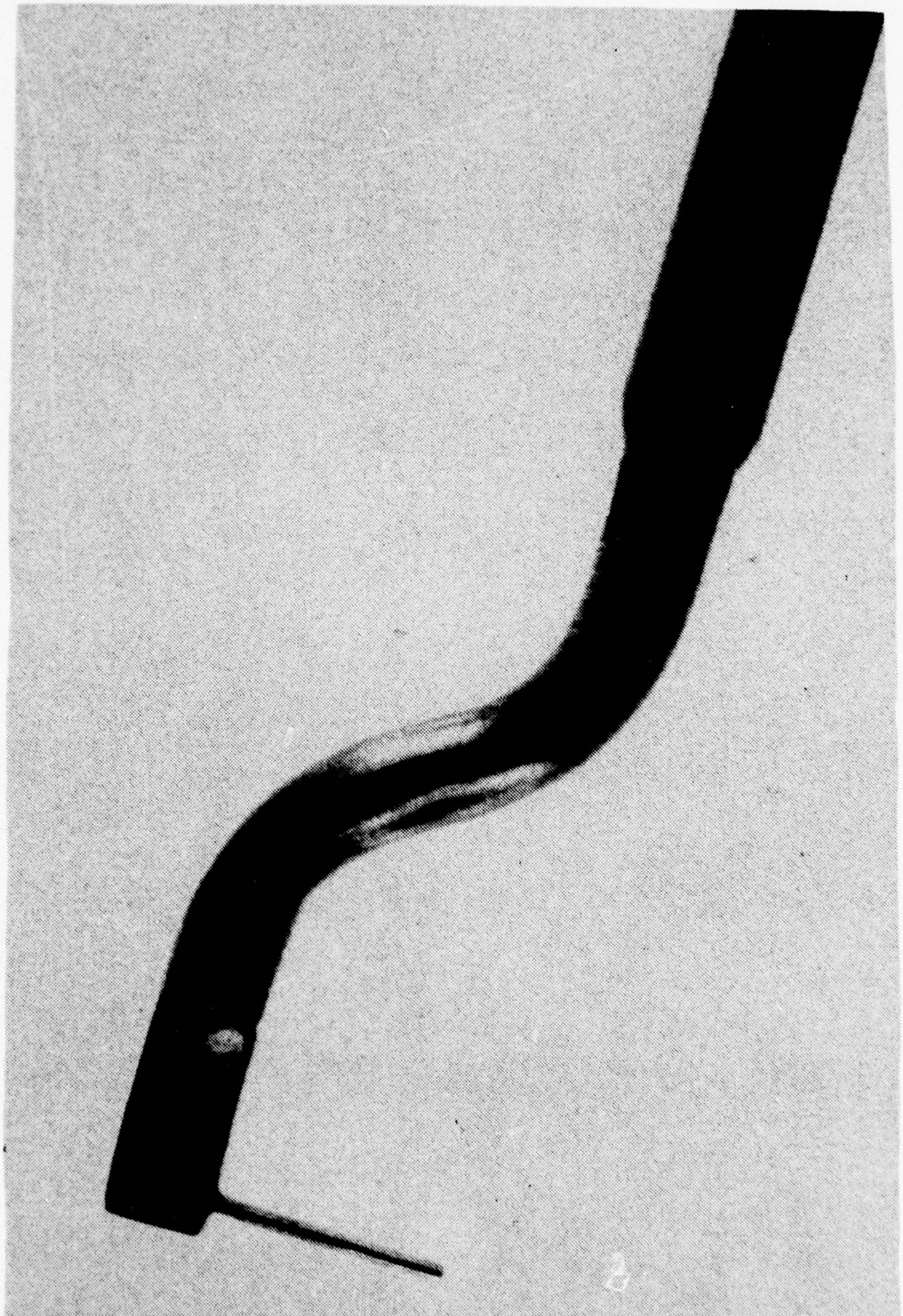


FIGURE A-1. PHOTOGRAPH OF 0.032" DIAMETER IMPACT PROBE

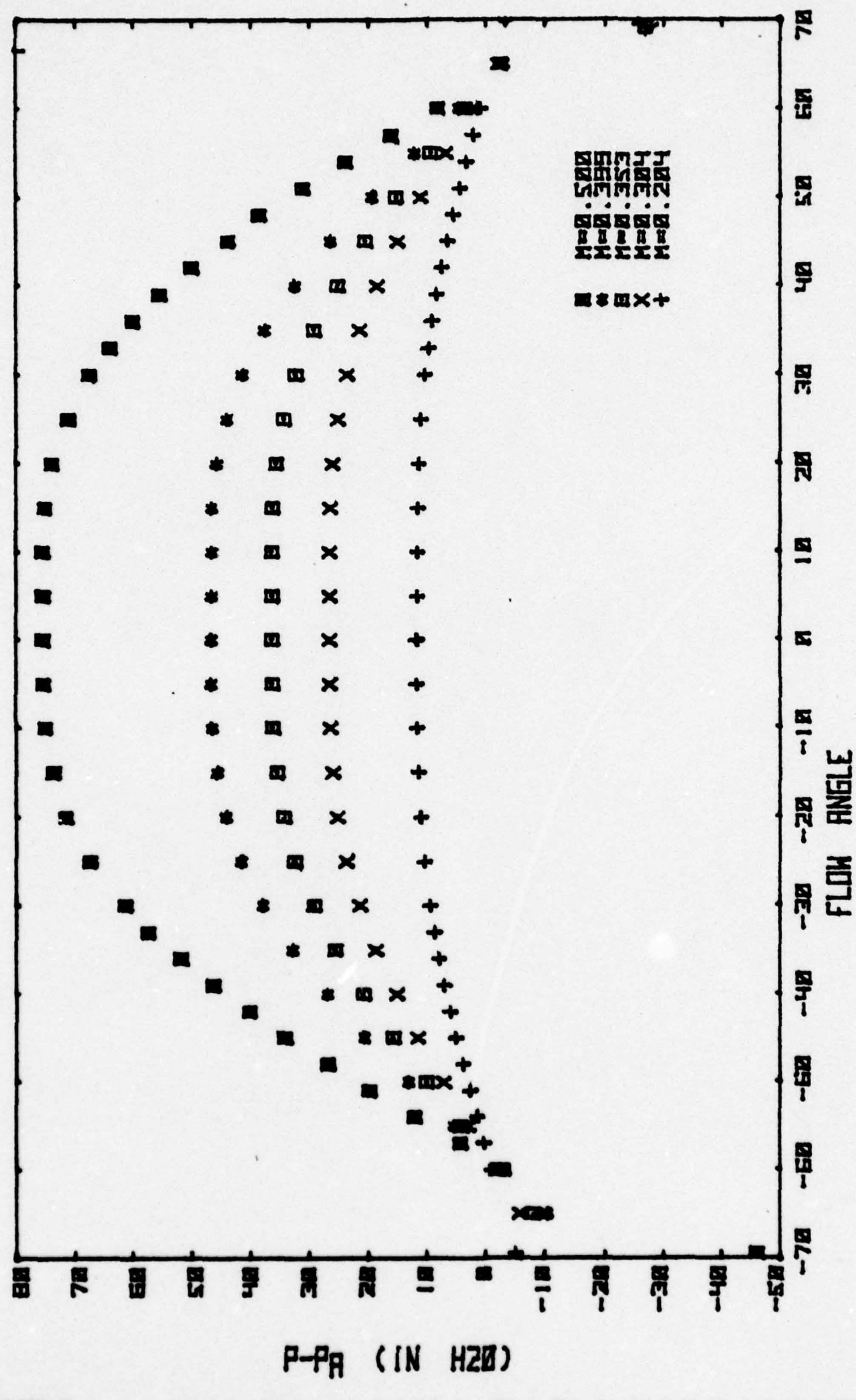


FIGURE A-2. CYLINDRICAL PNEUMATIC PROBE TEST RESULTS

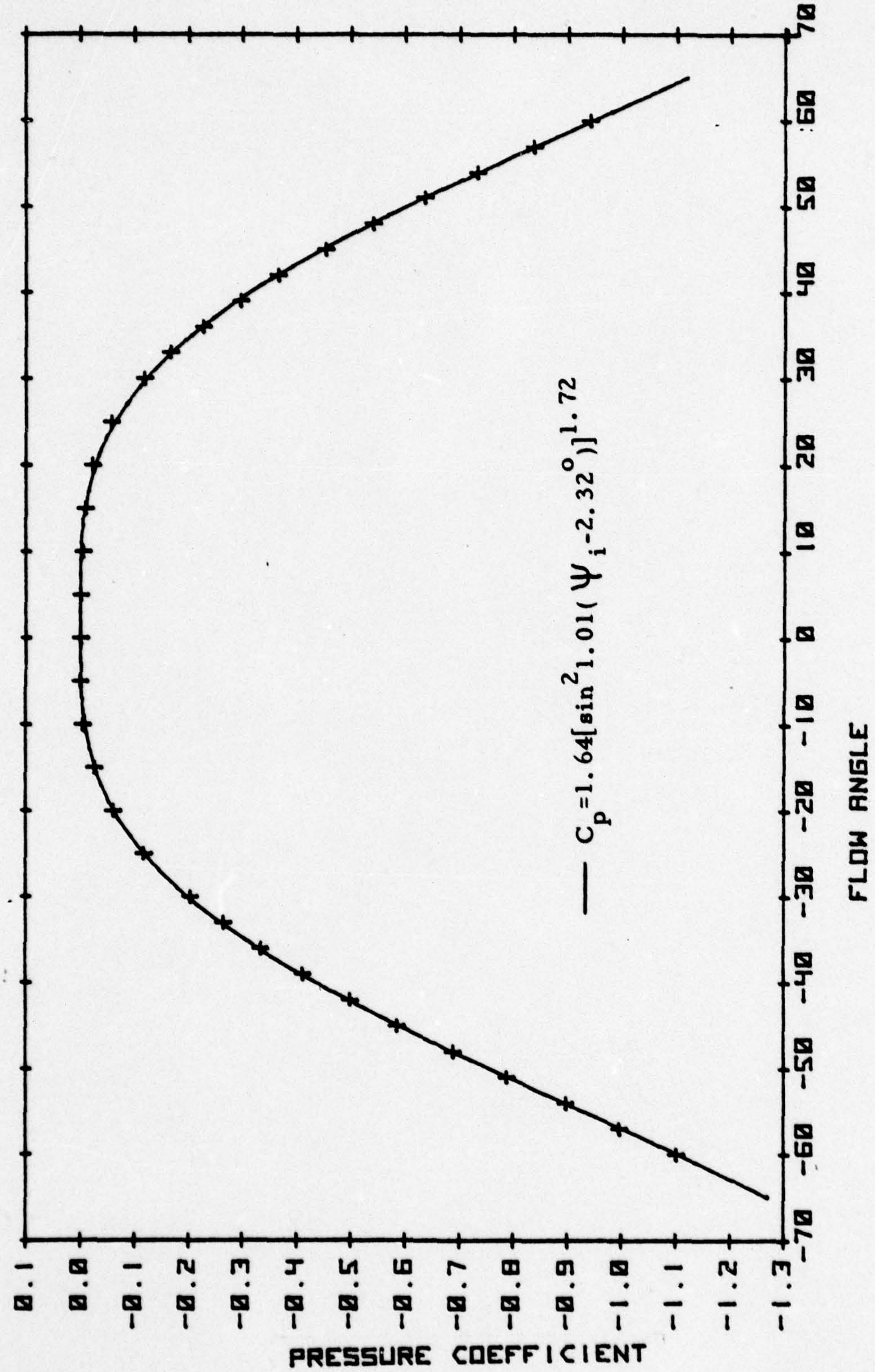


FIGURE A-3a. YAW ANGLE SURVEY FOR M = 0.204

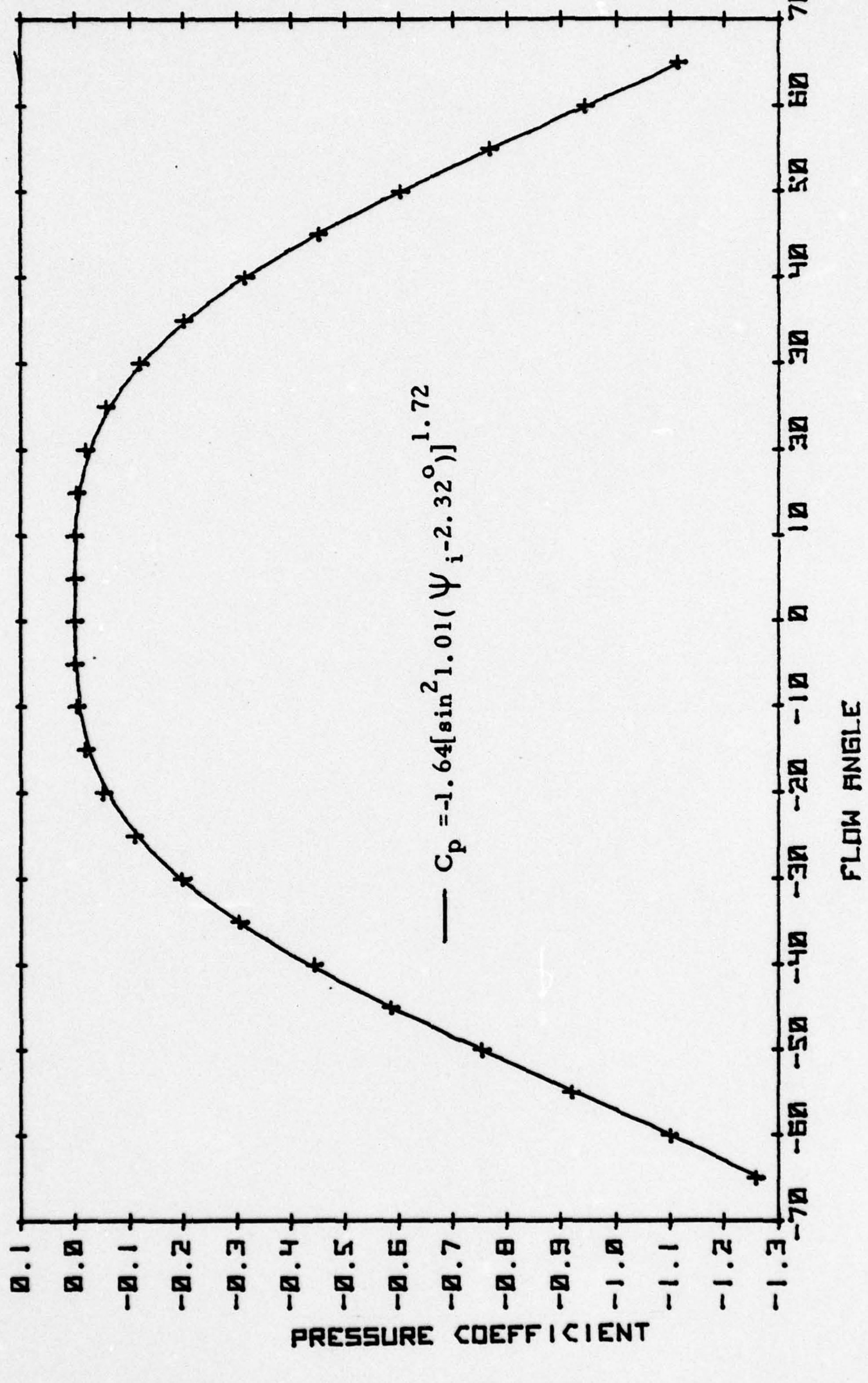


FIGURE A-3b. YAW ANGLE SURVEY FOR M = .304

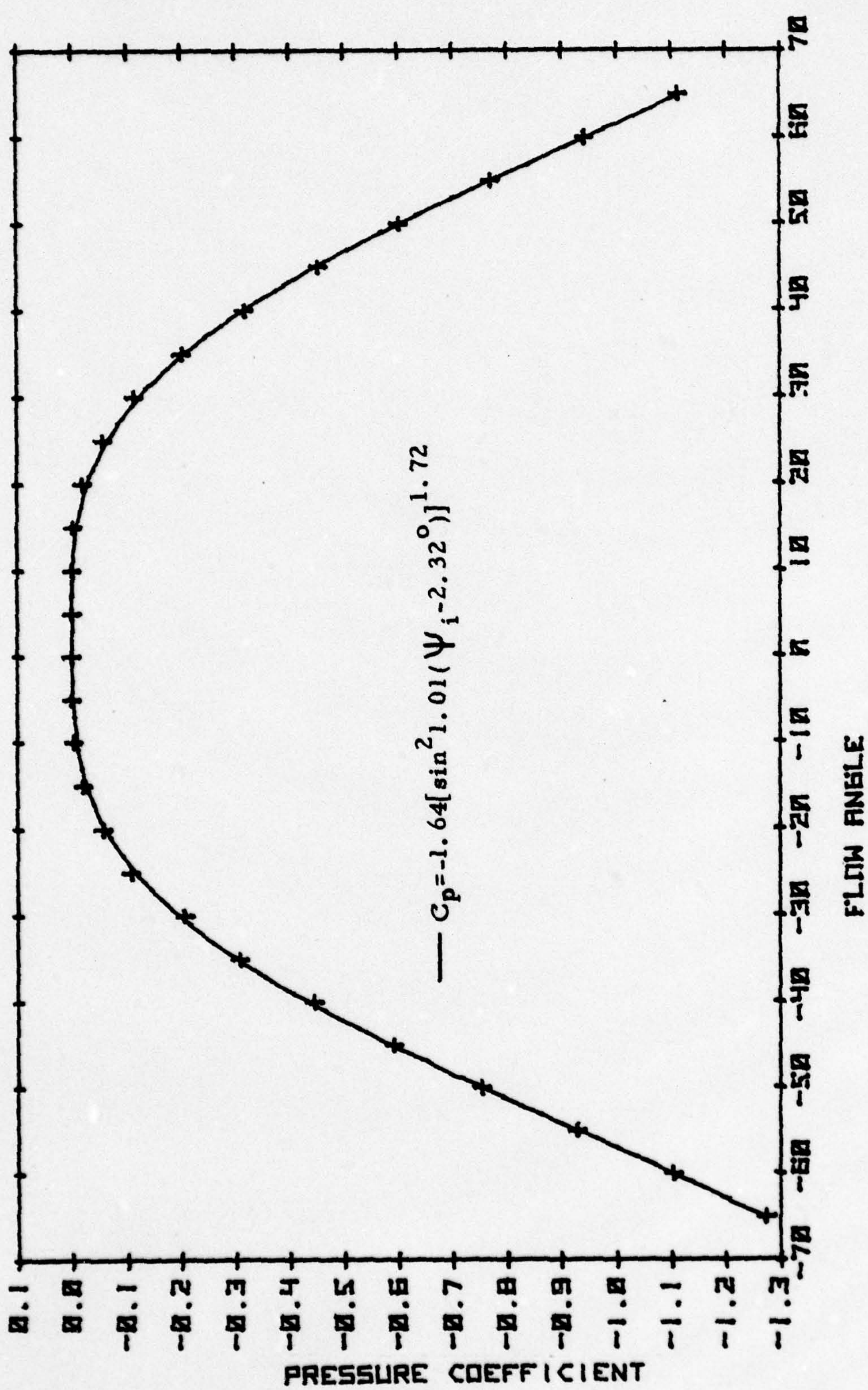


FIGURE A-3c. YAW ANGLE SURVEY FOR M = 0.353

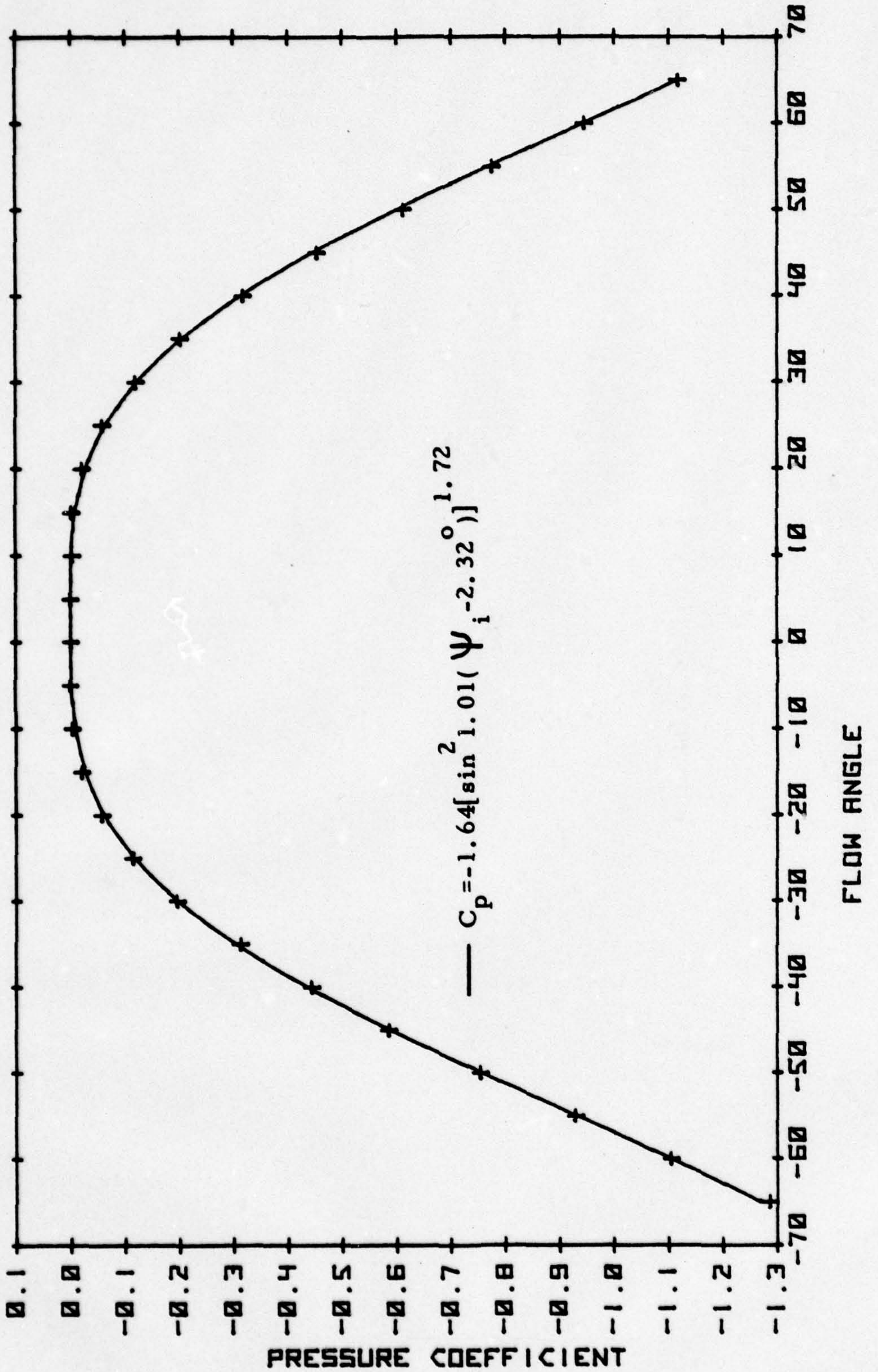


FIGURE A-3d. YAW ANGLE SURVEY FOR M = .399

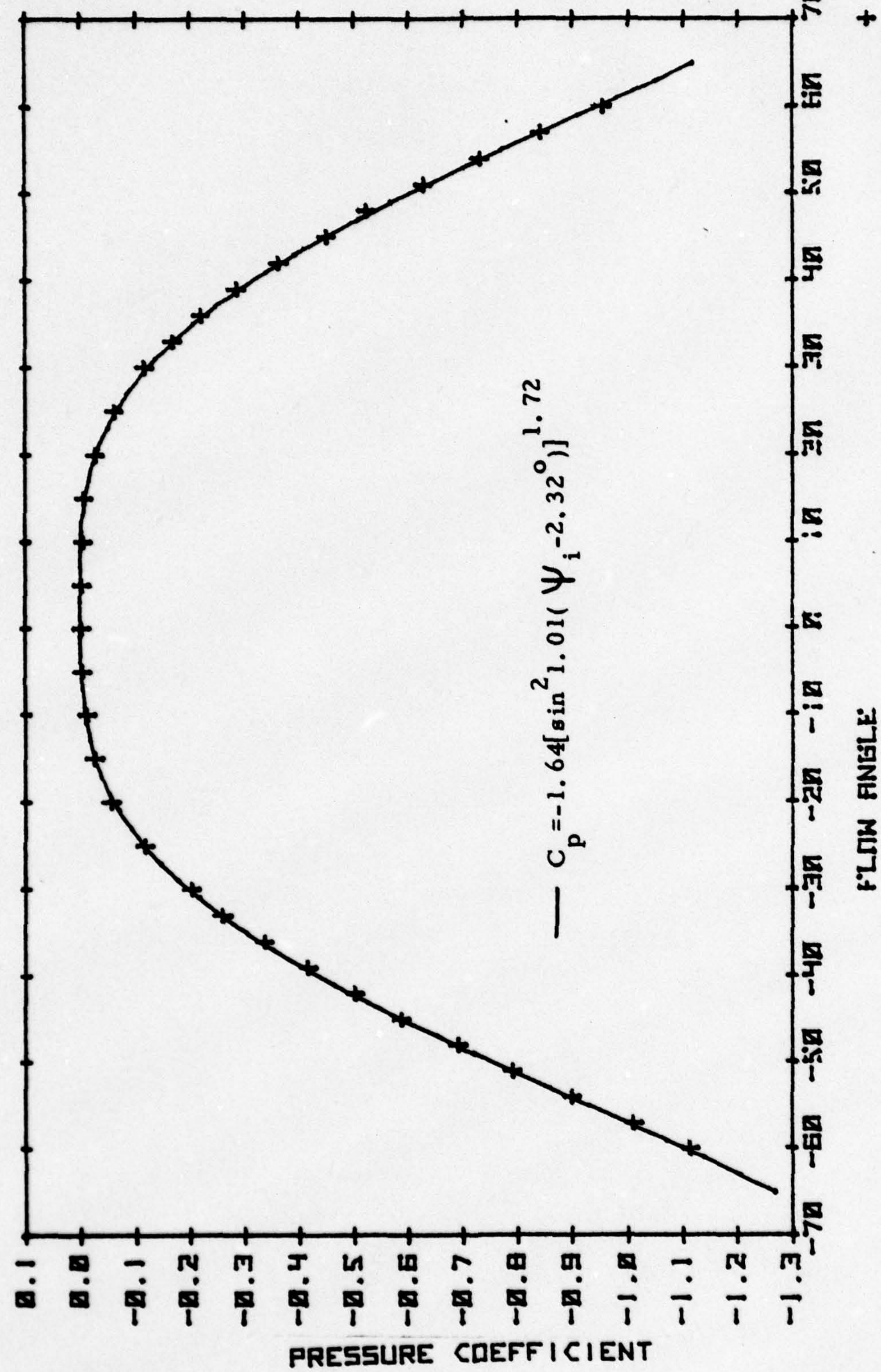


FIGURE A-3e. YAW ANGLE SURVEY FOR M = 0.500

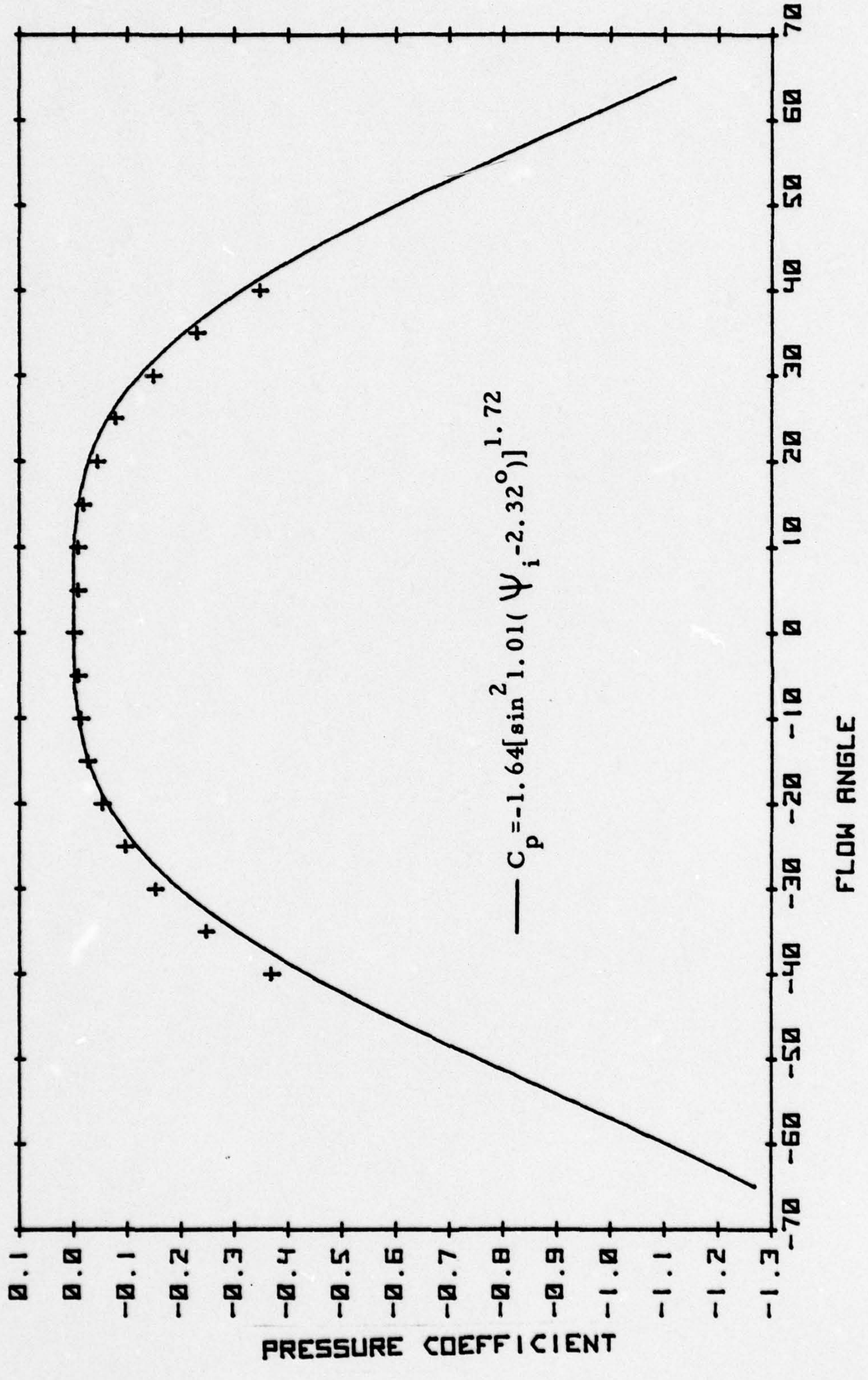


FIGURE A-3f. PITCH ANGLE SURVEY FOR M = .204

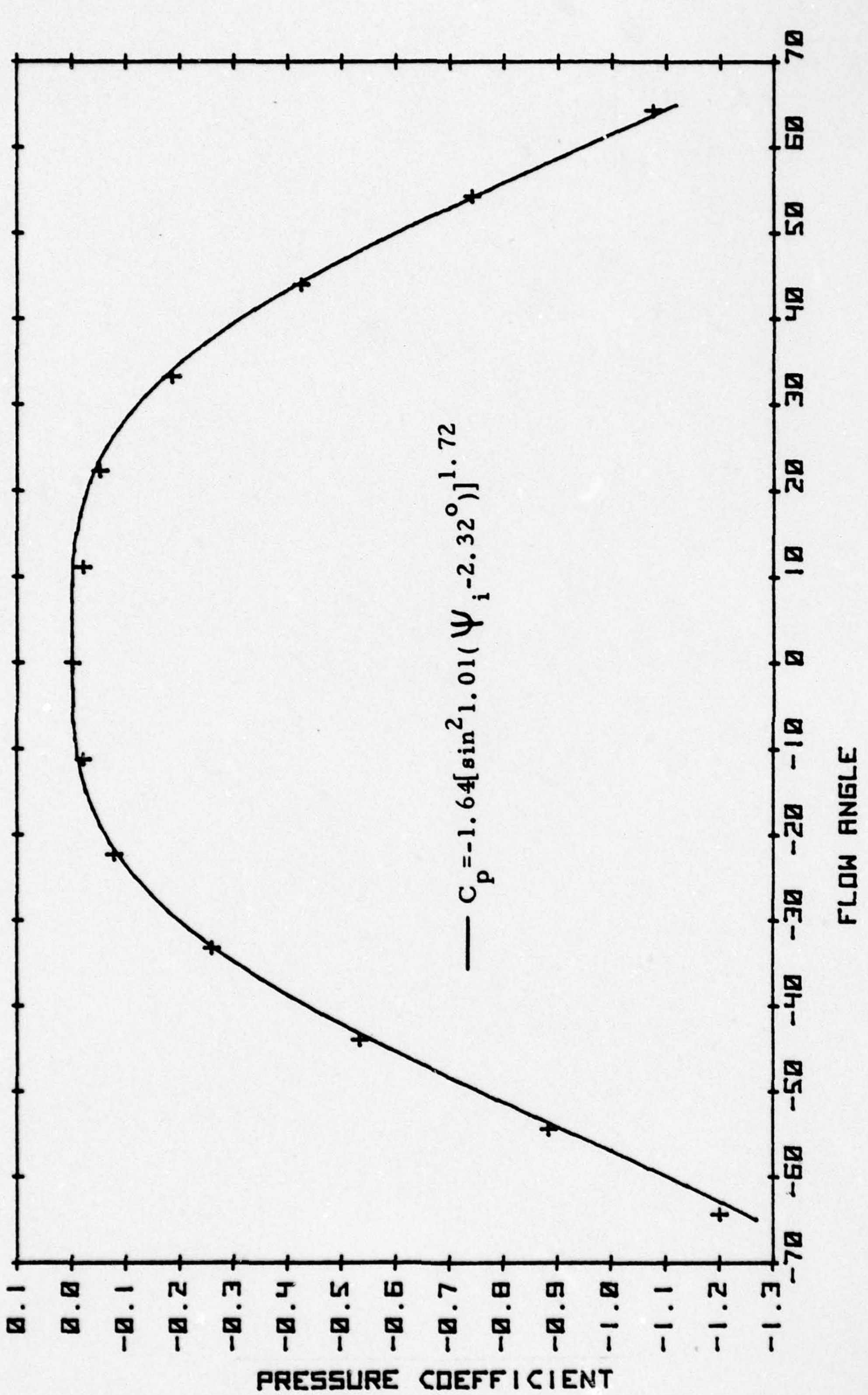


FIGURE A-3g. COMBINATION YAW AND PITCH ANGLE SURVEY FOR M = 0.204

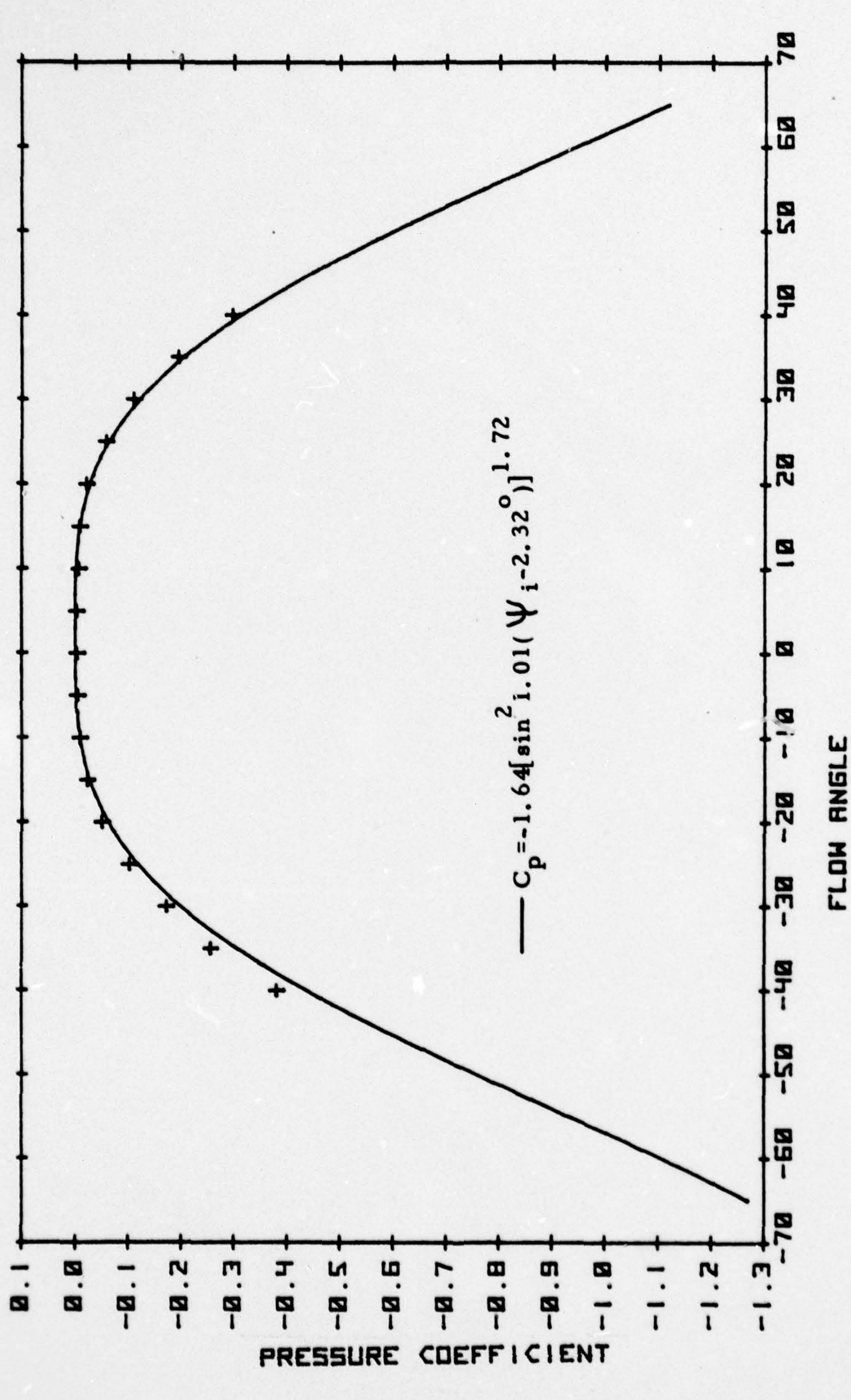


FIGURE A-3h. PITCH ANGLE SURVEY FOR M = .500

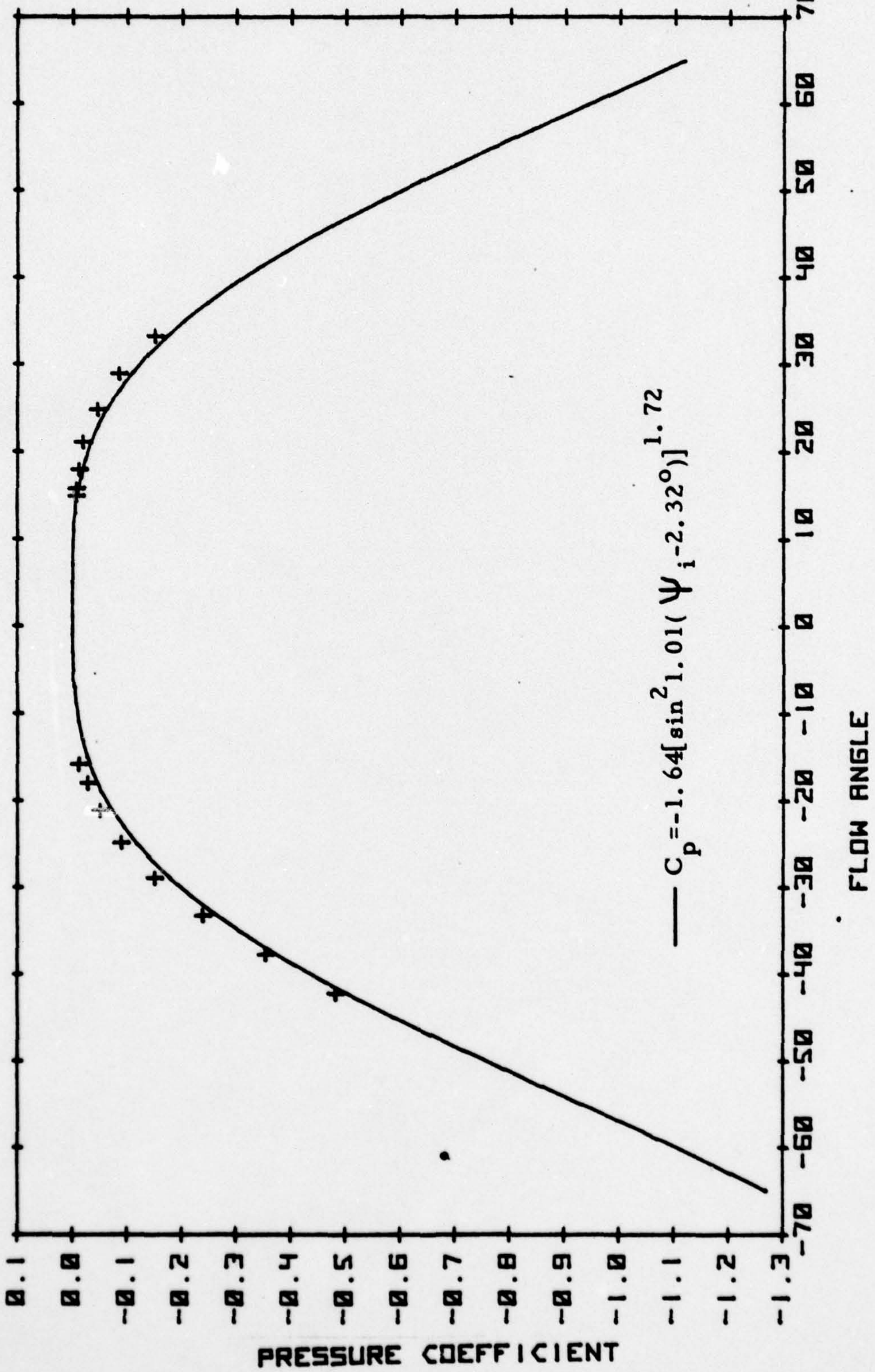


FIGURE A-3i. COMBINATION YAW AND PITCH ANGLE SURVEY FOR M = .500

APPENDIX B

LEAST SQUARES APPROXIMATION OF DATA USING

$$C_p = A(\sin^2 B(\Psi - \Psi_o))^N$$

1. Derivation of A, B, N and Ψ_o

From surveys of a cylindrical impact probe in a known flow, pressure data is reduced to a set of pressure coefficients $C_p i$ and flow angles, Ψ_i. For n sets of points (Cp_i, Ψ i) the coefficients A, B, N and Ψ_o form a least squares fit when the expression

$$Q = \sum_{i=1}^{n} (Cp_i - A(\sin^2 B(\Psi_i - \Psi_o))^N)^2 \tag{B1}$$

is minimized. A minimum value of Q is found when, simultaneously:

$$\frac{\partial Q}{\partial A} = -2 \sum_{i=1}^{n} \left\{ \begin{array}{c} [Cp_i - A(\sin^2 B(\Psi_i - \Psi_o))^N] \; . \\ [\sin^2 B(\Psi_i - \Psi_o)]^N \end{array} \right\} = 0 \tag{B2}$$

$$\frac{\partial Q}{\partial B} = 4AN \sum_{i=1}^{n} \left\{ \begin{array}{l} [C_{pi} - A(\sin^2 B(\Psi_i - \Psi_o))^N]. \; [\cos B(\Psi_i - \Psi_o)]. \\ [(\sin^2 B(\Psi_i - \Psi_o))^{N-1}]. \; [\sin B(\Psi_i - \Psi_o)].[\Psi_i - \Psi_o] \end{array} \right\} = 0 \tag{B3}$$

$$\frac{\partial Q}{\partial \Psi_o} = 4ANB \sum_{i=1}^{n} \left\{ \begin{array}{l} [C_{pi} - A(\sin^2 B(\Psi_i - \Psi_o))^N]. \; [\cos B(\Psi_i - \Psi_o)] \\ [(\sin^2 B(\Psi_i - \Psi_o))^{N-1}].[\sin B(\Psi_i - \Psi_o)] \end{array} \right\} = 0 \tag{B4}$$

$$\frac{\partial Q}{\partial N} = -2A \sum_{i=1}^{n} \left\{ \begin{array}{l} [C_{pi} - A(\sin^2 B(\Psi_i - \Psi_o))^N]. \; [(\sin^2 B(\Psi_i - \Psi_o))^N] \\ .[\ln(\sin^2 B(\Psi_i - \Psi_o))] \end{array} \right\} = 0 \tag{B5}$$

The simultaneous solution of equations B2, B3, B4 and B5 was achieved by a numerical procedure which sequentially solved each equation to find a value for the respective coefficient while the remaining coefficients were held constant. The procedure stepped through the solution of each equation in a cyclic manner until the simultaneous solution for A, B, N and Ψ_o was found. The solution of each equation for the value of the respective coefficient was achieved in an iterative manner using Newton's method for successive approximations. The derivative used to compute the iteration interval was defined as the linear slope of the function computed with the most recent pair of values for the iterated coefficient. The first two values of the function were obtained using a fixed interval to increment the coefficient. The solution was found when the value of the function was less than a specified small quantity.

The simultaneous solution of the four equations was obtained when the value of each respective partial derivative computed on the first iteration step was less than a specified small quantity.

No convergence criteria was applied to the sequential solution technique. After each individual coefficient was computed its value was held constant in the calculations for the other three coefficients.

The BASIC program "ITERATIVE LEAST SQUARES" for this method is listed in Table B-1. The computer time required to obtain a simultaneous solution for the coefficients A, B, N and Ψ_o depended on the number of data points used and the accuracy of the initial approximation for the

coefficients. Experience gained in using this procedure indicated that the following guidelines were appropriate:

a. Critical data points are in the ranges of positive and negative angles which define the nearly linear regions of the curve. The three nearly linear regions of the curve include, one centered about $\Psi = 0$, for which C_p is greater than -0.02, and the two sides with slopes which are equal but of opposite sign. The two sides are limited on one extreme by the maximum and minimum angles and on the other extreme by the angles at which significant curvature begins. Thus six data points, two in each of the nearly linear ranges, are required for a reasonable fit.

b. When selecting additional points consideration should be given to the areas where the most accurate characterization of the data is required.

c. The initial estimate of Ψ_o should be the angle, in degrees, at the center of the C_p vs Ψ curve.

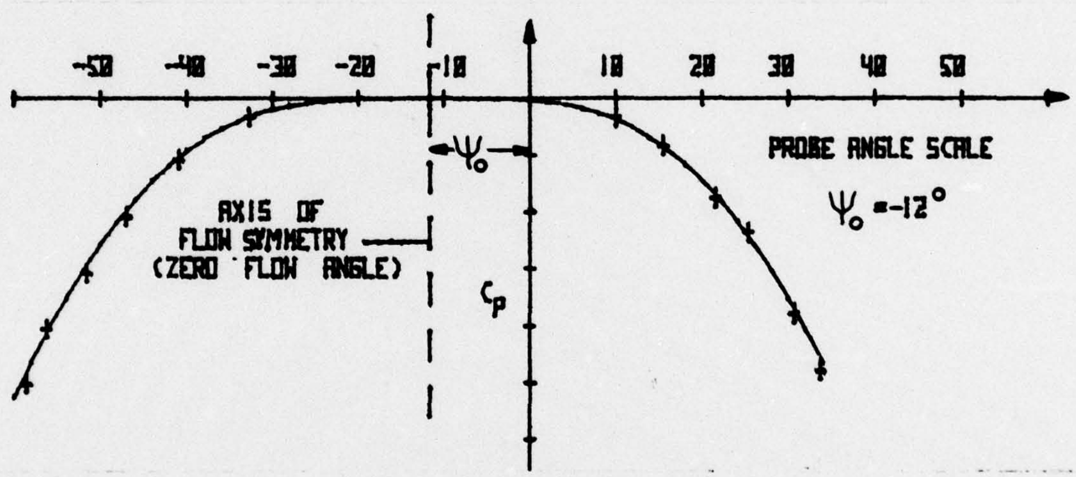
d. The initial approximation of B should be 1.0.

e. The initial approximation of A should be 0.5 less than the minimum C_p of the data.

f. The initial value of N should be estimated by dividing the angular width, in degrees, of the linear region for which C_p is greater than -0.02, by 18 degrees.

2. Determination of the Zero Yaw Angle

Using measurements of C_{pi} obtained from a cylindrical impact probe in a known flow, the coefficients A, B, N and Ψ_o are determined using the procedure described above. A, B, and N now characterize the probe with respect to Mach number and the actual angle of the flow to the probe axis. If Ψ is the angle of the probe axis with reference to some mechanical scale, Ψ_o is a measure of the difference between the zero on the mechanical scale and the probe angle at which the probe axis is aligned with the flow (zero flow angle). This is illustrated in the following sketch:



When A, B, and N are known, measurements taken in an unknown flow with the same probe can be used to find Ψ_o, which is the angle of the flow referenced to the mechanical scale. The pressure insensitivity of the cylindrical probes near the zero flow angle and the relationship in Equation A2 allows the assumption to be made that for small pitch angles the calculated zero flow angle of the probe will be equal to the zero yaw angle.

In order to determine the zero yaw angle, measurements of pressure are made at a series of probe angles about a reference value. Equal magnitudes on either side of the reference are taken (i.e. $\Psi = 0$, $\pm \Psi_i \ldots\ldots \pm \Psi_{max}$). The procedure to calculate the zero yaw angle of the flow is as follows:

a. Reduce pressure data to values of C_p. In a known flow this is simply to use Equation A4. In an unknown flow the C_p must be approximated since the total and static pressures are not known. A suitable approximation is obtained using the equation

$$C_p = A(\sin^2 B(\Psi_{max}))^N \frac{P_i - P_{max}}{P_{max} - (\frac{P_{min} + P_{nmin}}{2})} \tag{B6}$$

where; A, B and N are previously determined calibration constants,

P_i = ith impact pressure in the series

P_{max} = maximum P_i in the series

P_{min} = minimum P_i in the series

P_{nmin} = next to minimum P_i in the series

Ψ_{max} = absolute magnitude of the maximum and minimum probe angles in the survey.

This equation scales the pressure data to form a coefficient which has a variation similar in shape to the variation of Cp determined in the calibration test.

b. Determine Ψ_o from the data by solving equation B4 for Ψ_o while keeping A, B, and N constant. The resulting Ψ_o will be

the least squares solution for the zero yaw angle of the flow with respect to the mechanical probe angle scale.

A BASIC program "KAW40" which accepts pressure data and outputs the value of Ψ_o is listed in Table B2.

```
1  REM   ITERATIVE LEAST SQUARES---K A WINTERS-----IMPROVED 24JAN78
10  DIM A[2,50],T[20]
15  PRINT# 6;"CURVE FIT FOR CYLINDRICAL PROBE CHARACTERISTIC"
16  PRINT# 6
17  PRINT# 6;"DATA","PSI","CP"
19  LET R=57.2958
20  REM DATA INPUTS
21  PRINT "ENTER NUMBER OF CP VS PSI DATA POINTS"
22  INPUT I5
24  FOR I=1 TO I5
25  PRINT "ENTER PSI,CP FOR DATA POINT     "I
26  INPUT A[1,I],A[2,I]
27  PRINT# 6;I,A[1,I],A[2,I]
39  LET A[1,I]=A[1,I]/R
40  NEXT I
50  PRINT "ENTER INITIAL ESTIMATE OF A,B,N,AND YO"
51  INPUT A,B,N,YO
52  PRINT# 6
53  PRINT# 6"INITIAL ESTIMATE OF COEFICIENTS"
54  PRINT# 6;"A=   "A
55  PRINT# 6;"B=   "B
56  PRINT# 6;"N=   "N
57  PRINT# 6;"YO=  "YO
58  PRINT# 6
59  LET T1=0
60  PRINT T1,A,B,N,YO
69  LET T1=0
70  GOSUB 100
71  LET T1=T1+K
75  GOSUB 200
76  LET T1=T1+K
80  GOSUB 300
81  LET T1=T1+K
85  GOSUB 400
86  LET T1=T1+K
```

TABLE B-1. BASIC PROGRAM "ITERATIVE LEAST SQUARES"

```
87  IF T1<5 THEN 90
88  GOTO 60
90  PRINT# 6;"THE CALCULATED COEFICIENTS ARE"
91  PRINT# 6;"A=    "A
92  PRINT# 6;"B=    "B
93  PRINT# 6;"N=    "N
94  PRINT# 6;"YO=   "YO*R
99  STOP
100  REM ITERATION TO FIND  DQ/DYO=0
110  LET S=.00175
111  LET K=1
112  LET T[K]=0
113  LET E=.0001
119  LET F=0
120  FOR I=1 TO 15
122  LET Y1=A[1,I]-YO
124  LET S1=SIN(B*Y1)
126  LET C1=A[2,I]-A*(S1↑2)↑N
128  LET C2=(S1↑2)↑(N-1)
130  LET C3=COS(B*Y1)
132  LET F=F+Y1*C1*C2*C3
134  NEXT I
136  LET F=F*4*A*N*B
140  LET T[K]=F
145  IF ABS(T[K])<E RETURN
150  IF K<2 THEN 180
160  LET S=T[K]*S/(T[K-1]-T[K])
180  LET YO=YO+S
190  LET K=K+1
191  GOTO 112
200  REM ITERATION TO FIND DQ/DN=0
210  LET S=.05
211  LET K=1
212  LET E=.0001
213  LET T[K]=0
```

TABLE B-1 (continued)

```
219 LET F=0
220 FOR I=1 TO I5
222 LET Y1=A[1,I]-Y0
224 LET S1=SIN(B*Y1)
226 LET C1=A[2,I]-A*(S1↑2)↑N
228 LET C2=(S1↑2)↑N
230 LET C3=LN(S1↑2)
232 LET F=F+C1*C2*C3
234 NEXT I
236 LET F=(-2)*A*F
240 LET T[K]=F
245 IF ABS(T[K])<E RETURN
250 IF K<2 THEN 280
260 LET S=T[K]*S/(T[K-1]-T[K])
280 LET N=N+S
290 LET K=K+1
291 GOTO 213
300 REM ITERATION TO FIND DQ/DA=0
310 LET S=.1
311 LET K=1
312 LET E=.0001
313 LET T[K]=0
319 LET F=0
320 FOR I=1 TO I5
322 LET Y1=A[1,I]-Y0
324 LET S1=SIN(B*Y1)
326 LET C1=A[2,I]-A*(S1↑2)↑N
328 LET C2=(S1↑2)↑N
332 LET F=F+C1*C2
334 NEXT I
336 LET F=(-2)*F
340 LET T[K]=F
345 IF ABS(T[K])<E RETURN
350 IF K<2 THEN 380
360 LET S=T[K]*S/(T[K-1]-T[K])
```

TABLE B-1 (continued)

```
380  LET A=A+S
390  LET K=K+1
391  GOTO 313
400  REM ITERATION TO FIND DQ/DB=0
410  LET S=.05
411  LET K=1
412  LET E=.0001
413  LET T[K]=0
419  LET F=0
420  FOR I=1 TO 15
422  LET Y1=A[1,I]-YO
424  LET S1=SIN(B*Y1)
426  LET C1=A[2,I]-A*(S1↑2)↑N
428  LET C2=(S1↑2)↑(N-1)
430  LET C3=COS(B*Y1)
432  LET F=F+Y1*S1*C1*C2*C3
434  NEXT I
436  LET F=F*(-4)*A*N
440  LET T[K]=F
445  IF ABS(T[K])<E RETURN
450  IF K<2 THEN 480
460  LET S=T[K]*S/(T[K-1]-T[K])
480  LET B=B+S
490  LET K=K+1
491  GOTO 413
9999  END
```

TABLE B-1 (continued)

```
10 REM KAW40 LEAST SQUARES CURVE FITTING FOR YAW ANGLE 1/10/78
20 DIM A[3,50],T[20]
30 REM YAW DATA
31 REM THE FIRST 3 DATA POINTS ARE FOR MAX,MIN,AND ZERO ANGLES
40 PRINT "INPUT NUMBER OF DATA POINTS"
50 INPUT I5
51 DISP "INPUT MAX + ANGLE,PRESS";
52 INPUT A[1,1],A[3,1]
53 DISP "INPUT MIN -ANGLE,PRESS";
54 INPUT A[1,2],A[3,2]
55 DISP "INPUT ZERO ANGLE,PRESS";
56 INPUT A[1,3],A[3,3]
57 A9=A[3,1]/2+A[3,2]/2
60 FOR I=4 TO I5
70 LET R=180/PI
80 PRINT "FOR DATA POINT  "I"  INPUT ANGLE AND PRESS"
90 INPUT A[1,I],A[3,I]
101 NEXT I
105 FOR I=1 TO I5
110 LET A[1,I]=A[1,I]/R
120 NEXT I
130 LET K=1
140 LET A=-1.45947
150 LET B=1.07503
160 LET N=1.78747
161 C8=A*(SIN((A[1,1]-A[1,3])*B))↑(2*N)
162 FOR I=1 TO I5
163 A[2,I]=(A[3,I]-A[3,3])/(A[3,3]-A9)*(-C8)
164 PRINT "ANGLE="A[1,I]*R"  PRES="A[3,I]"  CP="A[2,I]
165 NEXT I
169 PRINT C8
```

TABLE B-2. BASIC PROGRAM "KAW 40"

```
170 LET YO=A[1,3]+0.1
180 LET S=0.00175
190 LET T[K]=0
200 FOR I=1 TO 15
210 LET C9=COS(B*(A[1,I]-YO))
220 LET C=A[2,I]-A*(1-C9↑2)↑N
230 LET B1=2*A*N*(A[1,I]-YO)*(1-C9↑2)↑(N-1)*C9*SIN(B*(A[1,I]-YO))
240 LET T[K]=C*B1*B/(A[1,I]-YO)+T[K]
250 NEXT I
260 LET T[K]=2*T[K]
270 IF ABS(T[K])<0.00001 THEN 340
280 IF K<2 THEN 310
290 LET S1=T[K-1]-T[K]
300 LET S=T[K]*S/S1
310 LET YO=YO+S
320 LET K=K+1
330 GOTO 190
340 PRINT "YO=    "YO*R
350 STOP
```

TABLE B-2 (continued)

AD-A057 342 NAVAL POSTGRADUATE SCHOOL MONTEREY CALIF F/G 13/7
DEVELOPMENT OF A METHOD FOR MEASURING VELOCITY AT THE EXIT OF A--ETC(U)
MAR 78 K A WINTERS

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APPENDIX C

DATA ACQUISITION SOFTWARE

C-1 BASIC PROGRAM "DATACQ"

The BASIC program "DATACQ" was written to acquire data using the Hewlett-Packard HP 21MX computer and peripherals described in Section III of this paper. It is modular in construction and can be used by a relatively inexperienced operator to sample real time data in a variety of modes. When used interactively as a multipurpose data acquisition control program, a question and answer format is used. For specialized data acquisition tasks, it can accept by merging, user subprograms which enter the modules (subroutines) in "DATACQ" in a non-interactive manner, thus eliminating the need for keyboard entries.

The key to the flexibility of "DATACQ' is the "Selector Module" which provides the control to access all data taking subroutines on command. A brief "user manual" is provided in this appendix to acquaint the user with the operation of "DATACQ". A program listing is provided in Table C-1.

C-2 USER MANUAL FOR BASIC PROGRAM "DATACQ"

A limited amount of information is provided in the remarks contained in the program. This users manual provides instructions for each function preprogrammed into "DATACQ". The first step in using "DATACQ" is to enter a user program that is written separately then merged into the main program. The user program must be written between lines 20 and

2000 to avoid overwriting other program lines. The simplest user program that can be used to acquire data is:

```
21    GOSUB 5000
22    STOP
```

This program transfers program control to the selector subroutine.

Subroutine 5000 - Selector Module

Upon calling subroutine 5000, the query

ENTER SELECT VARIABLE
?

will be displayed. A number corresponding to the desired module in the following list should be entered:

1 - Initialize calibration coefficient array

2 - Enter calibration coefficients from console

3 - On line probe calibration

4 - Synchronized sampling of data

6 - Free run sampling of data

Entry of any number other than the numbers listed here, 0 and 5, causes the query "ENTER SELECT VARIABLE" to be repeated. After a selected module has completed its operation "ENTER SELECT VARIABLE" will be repeated until a 0 or a 5 is entered, signaling the program execution to return to the user program.

Subroutine 4000 - Initialize Coefficient Array

This subroutine initializes the calibration coefficients for all data channels to have the values $x_0 = 0$ and $x_1 = 1$. As a result, samples of data taken on all channels will be displayed directly as voltages.

Subroutine 4050 - Enter Calibration Coefficients

This subroutine allows console entry of the calibration coefficients x_0 and x_1 for all 16 channels. Previous coefficients for the user selected channel are lost upon entry of the new coefficients.

Subroutine 3500 - Time

If the proper time of day was entered into the computer on startup, this subroutine returns with R1, T2, and T3 set to the time of day in hours, minutes past the hour, and seconds past the minute respectively. T is set to the time of day in seconds.

Subroutine 3600 - Time Scheduling

Caution - This subroutine may be called only once during "DATACQ" execution. A second call will result in an indefinite waiting state in program execution requiring an "abort" command to return computer control to the operator.

The purpose of this subroutine is to allow repetition of a task with start time, number of repetitions, and the interval between repetitions defined by the user. The task to be repeated must be programmed with the first program line number being 100, 300, 500, or 900 and a "Return" command as the last program line. Before calling the subroutine, the variable V9 must be set to a value equal to the first line number of the task to be repeated.

On completion of the required number of task repetitions, execution of a users program will continue with program line 30.

Caution - The user must insure that the time interval entered is sufficient to complete the task scheduled. Overlapping of scheduled tasks is not allowed.

Subroutine 2000 - RPACE Subroutine

This subroutine is used for synchronized sampling of a selected data channel. Before calling the subroutine the following variables must be defined.

A1 = 32768 + 256 * (Blade Pair) + SAMPLE LOCATION (0-255)

N1 = number of data samples to be taken at the specified location (Maximum value 2000)

N2 = number of channel to be sampled

The returned variables and their values are:

A2 = (15×10^6)/RPM

C(20, 100) = Data. The first N1 elements of this array (in row order) contain the values of the data samples.

CØ = The numerical average of N1 samples

Subroutine 2500 - Free run sampling

This subroutine is used for non-synchronized, "Free Run" sampling of a selected channel. Input variables N1 and N2 are defined as in the RPACE subroutine. The N1 samples requested are taken at 10 micro-second intervals. Output variables C(20, 100) and CØ are as defined in the RPACE subroutine.

Subroutine 7300 - Subroutine to sample pressure

This routine will sample channels designated as pressure channels and a channel designated as a reference pressure channel in the free run mode,and reduce the voltage data on-line to pressures using the expressions

$$P_r = (x_o)_r + (x_1)_r \cdot (\overline{E})_r$$

and

$$P_p = (x_o)_p + (x_1)_p \cdot (\overline{E})_p + Pr$$

where the subscript, r, refers to the reference channel and subscript p, refers to the pressure channel. x_o and x_1 are the calibration coefficients for the selected channel, $\overline{E}$ is the ensemble average of the sampled voltages, P_r is the reference pressure and P_p is the calculated pressure for the selected channel.

Inputs are defined interactively by answering the queries printed on the CRT console or, for non-interactive use, values may be pre-assigned to the listed variables and the subroutine entered at line 7340. The variables which must be defined in the non-interactive mode are:

E3-Channel # for the reference pressure or enter 16 for input at the console

E4-Number of free run samples desired on reference pressure channel

E5-Channel number of the pressure channel to be sampled

E6-Number of free run samples desired of the pressure channel

The subroutine prints the pressure, reference pressure, and pressure channel average voltage on the console CRT.

C-3 CONTROL PROGRAM FOR COMPRESSOR TEST

A program was written to be merged into "DATACQ" which caused data to be output on the tape punch and sent to the HP 9830 calculator. The program was used for the compressor test described in Section V. A listing of the control program is given in Table C-2.

```
1  REM REAL TIME AQUISITION PROGRAM----K A WINTERS-----1 MAR 78
2  REM THIS PROGRAM IS BUILT FROM MODULES  WHICH START WITH LINE 2000
3  REM BASIC PROGRAMS CAN BE WRITTEN SEPERATELY THEN MERGED FROM LINES
4  REM 20 THROUGH 1999
5  REM ARRAYS USED IN MODULE SUBROUTINES ARE DIMENSIONED IN LINE 19
6  REM USER ARRAYS SHOULD BE BY SEPARATE DIMENSION STATEMENT
10  REM      SUB 2000 FOR PACER SAMPLE, SUB 2500 FOR FREE RUN
11  REM       SUB 3000 FOR LINEAR LEAST SQUARES FIT,SUB 3500 FOR TIME
12  REM      SUB 3600 FOR SCHEDULED SAMPLING
13  REM     SUB 7000 FOR CALIBRATION
14  REM     SUB 4000 TO INITIALIZE COEFFICIENT ARRAY
15  REM     SUB 4050 TO ENTER COEFICIENTS
16  REM     SUB 7300 TO SAMPLE PRESSURE
17  REM     SUB 7500 PACED SAMPLING
18  REM SUB 5000 FOR SELECTOR
19  DIM B[16],C[20,100],T[16,2],D[255]
```

TABLE C-1. BASIC PROGRAM "DATACQ"

```
2000 REM RPACE SUBR---REF WEST THESIS ON RPACE ENTER WITH A1=IBLAD
2002 REM IBLAD=32768+256*BLADE PAIR NUMBER+SAMPLE PULSE LOCATION
2010 REM R5610 SUBROUTINE IS INCLUDED,ENTER WITH N1=# OF SAMPLES
2020 REM ,N2=CHANNEL NUMBER,M =MODE(0=PACER,4=FREE RUN)
2030 REM ***NOTE LIMITS  0<N1<=2000,0<=N2<=15
2040 REM SUBROUTINE RETURNS WITH DATA IN ARRAY C ,AND A2=IRPM
2041 REM ALSO RETURNED IS CO=AVG VALUE OF N1 SAMPLES(AVGS 56 VALUES/SEC
2102 REM SET MODE TO PACER
2103 LET M=0
2110 RPACE(A1,A2,A3)
2120 R5610(7,C[1,1],N1,N2,M,B[1])
2121 REM CO=AVG OF N1 SAMPLES TAKEN
2122 LET CO=0
2123 IF (N1/100)=INT(N1/100) THEN 2130
2124 LET I8=INT(N1/100)+1
2125 LET J8=N1-100*(I8-1)
2126 GOTO 2140
2130 LET I8=N1/100
2131 LET J8=100
2140 FOR I7=1 TO I8
2150 FOR J7=1 TO 100
2160 LET CO=CO+C[I7,J7]
2165 IF I7<I8 THEN 2180
2170 IF J7=J8 THEN 2190
2180 NEXT J7
2181 NEXT I7
2190 LET CO=CO/N1
2200 RETURN
2210 REM
2220 REM
2230 REM
```

TABLE C-1 (continued)

```
2500 REM FREE RUN SAMPLING MODE=4 SAMPLES TAKEN EVERY 10 MICROSEC
2510 REM SEE REMARKS LINE 2010-2040 FOR VARIABLE DEFINITIONS
2550 LET M=4
2560 GOSUB 2120
2561 REM
2562 REM
2563 REM
2600 RETURN
3000 REM LEAST SQUARES ROUTINE -- INSERT IN ITERATION LOOP
3010 REM  GOSUB 3050 WITH DATA X,Y
3020 REM AFTER EXITING ITERATION LOOP GOSUB 3200 TO COMPUTE
3030 REM X=0 INTERCEPT(X0), AND SLOPE OF LINEAR FIT(X1)
3031 REM*****SAMPLE OF USE OF LINEAR LEAST SQUARES SUBROUTINES
3032 REM*****LET N=0  (N MUST BE SET=0 BEFORE ENTERING FOR FIRST TIME
3033 REM*****FOR I= 1 TO END
3034 REM*****INPUT X,Y
3035 REM*****GOSUB 3050
3036 REM*****NEXT I
3037 REM*****GOSUB 3200
3038 REM*****PRINT"INTERCEPT="X0"SLOPE="X1
3040 REM SUBROUTINE VARIABLES N,X,X1,X2,Y,Y1,Y2,Z
3050 IF N>0 THEN 3070
3060 LET X1=X2=Y1=Y2=Z=0
3070 LET N=N+1
3080 LET X1=X1+X
3090 LET X2=X2+X↑2
3100 LET Y1=Y1+Y
3110 LET Z=Z+X*Y
3120 RETURN
3200 LET Y2=(N*Z-X1*Y1)/(N*X2-X1↑2)
3210 LET X0=(Y1-Y2*X1)/N
3220 LET X1=Y2
3230 LET N=0
3240 RETURN
3250 REM
3260 REM
3270 REM
```

TABLE C-1 (continued)

```
3500 REM TIME SAMPLE  SUBROUTINE RETURNS WITH
3510 REM T1=HOURS,T2=MINUTES,T3=SECONDS
3520 TIME(T)
3530 LET T1=INT(T/3600)
3540 LET T2=INT((T/3600-T1)*60)
3550 LET T3=INT(T-T1*3600-T2*60)
3560 RETURN
3570 REM
3580 REM
3590 REM
3600 REM-TIMED SAMPLING -GOSUB 3600 TO SCHED START TIME,AND INTERVAL
3620 GOSUB 3500
3630 PRINT "TIME NOW";T1*10000+T2*100+T3
3640 PRINT "ENTER START TIME,NUMBER OF SAMPLES,TIME BETWEEN SAMPLES"
3650 INPUT T4,N9,T5
3670 LET I9=1
3679 TRNON(3685,T4)
3680 GOTO 3680
3685 LET T4=T4+T5
3690 IF T4-INT(T4/100)*100 >= 60 LET T4=T4+40
3700 IF T4-INT(T4/10000)*10000 >= 6000 LET T4=T4+4000
3710 IF T4 >= 240000 LET T4=T4-240000
3715 LET I9=I9+1
3720 IF V9=100 GOSUB 100
3721 IF V9=300 GOSUB 300
3722 IF V9=500 GOSUB 500
3723 IF V9=700 GOSUB 700
3724 IF I9>N9 THEN 30
3739 TRNON(3685,T4)
3740 RETURN
```

TABLE C-1 (continued)

```
4000 REM CALIBRATION COEF CHANNELS 0-15 ARRAY T(CHN#+1,2)
4010 REM SUB 4040 INITIALIZES WITH X0=0,X1=1
4011 REM SUB 4050 INPUTS COEF FROM KEYBOARD
4040 FOR I=1 TO 16
4042 LET T[I,1]=0
4044 LET T[I,2]=1
4046 NEXT I
4048 RETURN
4050 PRINT "INPUT CHAN# OR NUMBER>15 TO EXIT"
4060 INPUT I
4065 IF I>15 RETURN
4070 PRINT "INPUT X0,X1"
4080 INPUT T[I+1,1],T[I+1,2]
4090 GOTO 4050
4095 RETURN
5000 REM ;   MODULE SELECTOR
5010 REM      0=RETURN TO USER PROGRAM
5020 REM      1=INITIALIZE COEF ARRAY
5030 REM      2=ENTER COEF
5040 REM      3=CALIBRATION
5050 REM     4=PACED SAMPLES
5060 REM     5=RETURN
5070 REM     6 =SAMPLE TRANSDUCER
5100 PRINT "ENTER SELECT VARIABLE"
5110 INPUT V8
5120 IF V8=0 THEN 5200
5130 IF V8=1 GOSUB 4000
5140 IF V8=2 GOSUB 4050
5150 IF V8=3 GOSUB 7000
5155 IF V8=4 GOSUB 7500
5156 IF V8=5 RETURN
5157 IF V8=6 GOSUB 7300
5190 GOTO 5100
5200 RETURN
```

TABLE C-1 (continued)

```
7000  REM PROBE CALIBRATION ROUTINE ----
7010  REM LINEAR LEAST SQUARES IS USED--PROBE PRES-REF PRES=X0+X1*VOLTS
7050  PRINT "NUMBER OF CALIBRATION POINTS"
7051  INPUT E9
7060  PRINT "ENTER CHANNEL NUMBER OF PROBE"
7061  INPUT E8
7070  PRINT "ENTER CHANNEL NUMBER FOR REF PRES OR  16=CONSOLE"
7071  INPUT E7
7080  PRINT "ENTER CHANNEL NUMBER FOR FACE PRESSURE OR 16=CONSOLE"
7081  INPUT E6
7089  PRINT# 6;"CALIBRATION OF CHANNEL #"E8
7090  PRINT# 6;"FACE PRESS      REF PRESS     VOLTS      PFACE-PREF"
7092  LET N=0
7094  REM SET N1=# OF SAMPLES IN FREE MODE
7100  FOR I6=1 TO E9
7105  PRINT "WHEN PRESS IS SET ENTER 1 TO SAMPLE"
7106  INPUT D9
7110  REM SAMPLE REF PRESS
7111  IF E7>15 THEN 7120
7113  LET N2=E7
7114  LET N1=300
7115  GOSUB 2500
7117  LET P7=T[E7+1,1]+T[E7+1,2]*C0
7119  GOTO 7130
7120  PRINT "INPUT REF PRESS"
7121  INPUT P7
7130  REM SAMPLE CALIBRATED FACE PRESSURE
7131  IF E6>15 THEN 7140
7133  LET N2=E6
7134  LET N1=300
7135  GOSUB 2500
7137  LET P6=T[E6+1,1]+T[E6+1,2]*C0
7139  GOTO 7150
7140  PRINT "ENTER FACE PRESSURE"
7141  INPUT P6
7150  LET N2=E8
7155  LET N1=1681
```

TABLE C-1 (continued)

```
7160 GOSUB 2500
7170 LET X=CO
7180 LET Y=P6-P7
7190 PRINT# 6;P6,P7,X,Y
7200 GOSUB 3050
7210 NEXT I6
7220 PRINT# 6
7230 GOSUB 3200
7240 PRINT# 6;"FOR"E9"POINTS----XO="XO"X1="X1
7250 PRINT# 6
7260 LET T[E8+1,1]=XO
7270 LET T[E8+1,2]=X1
7290 RETURN
7300 REM  SUBROUTINE TO SAMPLE PRESSURE
7301 REM      RETURNS WITH P=PRESSURE,P1=REF PRESSURE
7302 REM   INTERACTIVE ENTRY POINT SUB 7300
7303 REM   PREDEFINTED ENTRY POINT SUB 7340;E5=CHAN,E3=R PRES CH,E4=#
7304 REM E2=# OF SAMPLES REF PRES
7320 PRINT "ENTER CHANNEL # AND #OF SAMPLES"
7321 INPUT E5,E4
7330 PRINT "PREF ENTER CH# OR 16(CONSOLE INPUT) OR 17(PREF=PATM)"
7331 INPUT E3
7332 IF E3>15 THEN 7340
7335 PRINT "ENTER # OF SAMPLES REF PRES"
7336 INPUT E2
7340 IF E3>15 THEN 7350
7342 LET N2=E3
7344 LET N1=E2
7346 GOSUB 2500
7348 LET P1=T[E3+1,1]+T[E3+1,2]*CO
7349 GOTO 7370
7350 IF E3>16 THEN 7369
7361 INPUT P1
7365 GOTO 7370
7369 LET P1=0
7370 LET N1=E4
7380 LET N2=E5
7390 GOSUB 2500
7400 LET P=T[E5+1,1]+T[E5+1,2]*CO+P1
7405 PRINT "PRES ="P,"VOLTS="CO,"REF PRES="P1
7410 RETURN
```

TABLE C-1 (continued)

```
7500  REM  SUBROUTINE FOR PACED SAMPLING
7501  REM  AVG VOLTAGE FOR EACH DISCRETE SAMPLE POINT IN ARRAY D(POINT)
7502  REM   INTERACTIVE ENTRY SUB 7500
7503  REM   PREDEFINED ENTRY 7540;J2=BL PR,J3=SAM SP,J4=1 PER REV,N1,N2
7510  PRINT "ENTER NUMBER OF SAMPLES, CHAN#"
7511  INPUT N1,N2
7520  PRINT "ENTER 0 FOR EVERY BLADE,OR 1 FOR EVERY REV"
7521  INPUT J4
7530  PRINT "ENT BLADE PAIR AND SAMP SPACE# OR 999=EVERY OTHER SPACE"
7531  INPUT J2,J3
7540  IF J3<256 THEN 7610
7550  FOR J3=1 TO 128
7560  LET A1=J4*32768+J4*J2*256+2*J3
7570  GOSUB 2000
7580  LET D[J3]=C0
7590  NEXT J3
7600  RETURN
7610  LET A1=J4*32768+J4*J2*256+J3
7620  GOSUB 2000
7630  LET D[J3+1]=C0
7640  RETURN
9999  END
```

TABLE C-1 (continued)

```
50  GOSUB 5000
100  REM DATA OUTPUT
110  PRINT "INPUT ANGLE FOR KULITE PROBE"
111  INPUT A
120  PRINT# 4;A
130  PRINT# 8;A
140  PRINT "INPUT KULITE CHANNEL NUMBER"
141  INPUT D8
150  PRINT "INPUT REFERENCE PRESSURE"
151  INPUT P1
180  PRINT# 6;"KULITE AND PNEUMATIC SET AT "A" DEGREES"
185  LET P8=0
190  FOR I=1 TO 128
200  LET P=T[D8+1,1]+T[D8+1,2]*D[I]+P1
210  LET P8=P8+P
220  PRINT# 4;I
230  PRINT# 4;P
240  PRINT# 8;I
250  PRINT# 8;P
260  NEXT I
270  LET P8=P8/128
280  PRINT# 6;"PACED TIME AVG = "P8
281  PRINT# 6;"REFERENCE PRESSURE = "P1
290  PRINT "DATA TRANSFERED AND PUNCHED"
300  PRINT
310  GOTO 50
```

TABLE C-2. COMPRESSOR TEST CONTROL PROGRAM

APPENDIX D

DERIVATION OF MULTIPLE SENSOR PROBE CALIBRATION USING SINGLE IMPACT PROBE CHARACTERISTICS

Using the characteristics of the cylindrical impact probe discussed in Appendix A, which was similar in geometry to the individual sensors of the Dodge probe, a calibration was derived for the Dodge probe.

The following definitions were used:

P_1 - Pressure at the Dodge P_1 sensor

P_{23} - Average of the Dodge P_2 and P_3 sensor pressures

P_4 - Pressure at the Dodge P_4 sensor

ψ_i - The angle of the flow with respect to the sensor axis

α - Yaw angle with respect to axial direction

ϕ - Pitch angle with respect to the plane normal to the probe shaft

M - Mach number

P_s - Static pressure

P_t - Total pressure

γ - Ratio of specific heats (γ = 1.4 was used)

In Appendix A it was shown that, for a single impact tube, the pressure coefficient defined as

$$C_p = \frac{P_i - P_t}{\frac{\gamma}{2} P_s M^2} \quad (1)$$

was closely approximated by the expression

$$C_p = A\,[\sin^2 B(\Psi_i - \Psi_o)]^N \tag{2}$$

where the flow angle Ψ_i was determined from pitch and yaw angle by

$$\Psi_i = \cos^{-1}(\cos\alpha_i \cos\phi_i) \tag{3}$$

For the Dodge probe, when rotated to balance the pressures at sensors P_2 and P_3, the following table lists the values of the angles for each of the sensors

	Dodge sensor 1	2-3	4
α_i	0	$\bar{\alpha}$	0
ϕ_i	ϕ	ϕ	$\phi-\bar{\phi}$
Ψ_i	ϕ	$\cos^{-1}(\cos\bar{\alpha}\cos\phi)$	$\phi-\bar{\phi}$

where

$\bar{\alpha}$ = angle between axis of sensor 2 or 3 and sensor 1

$\bar{\phi}$ = angle between axes of sensor 4 and sensor 1

The quantities which have been used previously to represent the probe characteristics are:

$$\bar{\gamma} = \frac{P_1 - P_4}{P_1 - P_{23}} \tag{4}$$

and

$$\beta = \frac{P_1 - P_{23}}{P_1} \tag{5}$$

Using equation (2) in equation (4)

$$\bar{\gamma} = \frac{C_{p1} - C_{p4}}{C_{p1} - C_{p23}} = \frac{[\sin^2 B\,\Psi_1]^N - [\sin^2 B\,\Psi_4]^N}{[\sin^2 B\,\Psi_1]^N - [\sin^2 B\,\Psi_{23}]^N}$$

Using equation (3),

$$\bar{\gamma} = \frac{[\sin^2 B\phi]^N - [\sin^2 B(\phi-\phi)]^N}{[\sin^2 B\phi]^N - [\sin^2 B(\cos^{-1}\langle\cos\bar{\alpha}\ \cos\phi\rangle\ )]^N} \tag{6}$$

Note that if the pressure coefficient, C_p is independent of Mach number, then equation (6) gives pitch angle (ϕ) in terms of sensor measurements ($\bar{\gamma}$). There must be no interference between sensors, however for equation 6 to describe the probe characteristics correctly. Using Equation (5)

$$\beta = \frac{C_{p1} - C_{p23}}{C_{p1} + \frac{P_t}{\frac{\gamma}{2} P_s M^2}} = \frac{A[\sin^2 B\phi]^N - A\,[\sin^2 B(\cos^{-1}\langle\cos\bar{\alpha}\cos\phi\rangle\ )]^N}{A[\sin^2 B\phi]^N - \frac{2}{\gamma M^2}\,[1 + \frac{\gamma-1}{2} M^2]} \tag{7}$$

Defining

$$x = \frac{2}{\gamma M^2}\,[\,1 + \frac{\gamma-1}{2}\ M^2]^{\gamma/\gamma-1} \tag{8}$$

equation (7) may be written

$$x = A[(\frac{1}{\beta} - 1)\,(\sin^2\ \langle B\phi\rangle\ )^N - \frac{1}{\beta}\,(\sin^2 B(\cos^{-1}\ \langle\cos\bar{\alpha}\cos\phi\rangle\ ))^N] \tag{9}$$

If the pitch angle is known, equation (9) gives the Mach number, M, for a measured value of β.

Alternatively if we define

$$\delta = \beta\bar{\gamma} = \frac{C_{p1} - C_{p4}}{C_{p1} + x} \tag{10}$$

then equation (9) becomes:

$$x = A\,[(\frac{1}{\delta} - 1)\,(\sin^2\ \langle B\phi\rangle\ )^N - \frac{1}{\delta}(\sin^2 B\ \langle\phi-\bar{\phi}\rangle\ )^N] \tag{11}$$

Equations (6), (8), (9) and (11) were used to derive a calibration for the Dodge probe. The coefficients A, B, and N which represent the characteristics of the single impact tube similar to the sensors of the Dodge probe were determined as in Appendix B.

From measurements taken in a known flow at zero pitch angle ($\phi = 0$) with the Dodge probe the quantities $\beta, \bar{\gamma}$ and δ were calculated using equations 4, 5 and 10.

The angle $\bar{\alpha}$ was computed from equation 9.

First, x was calculated from equation (8) using the measured Mach numbers. Then from equation (9),

$$x = \frac{A(\sin^2 B\bar{\alpha})^N}{\beta}$$

or

$$\bar{\alpha} = \frac{\sin^{-1}\left[\left(\frac{x\beta}{-A}\right)^{\frac{1}{2N}}\right]}{B}$$

The angle $\bar{\phi}$ was computed similarly from equation 11:

$$\bar{\phi} = \frac{\sin^{-1}\left[\left(\frac{x\delta}{-A}\right)^{\frac{1}{2N}}\right]}{B}$$

Having established $\bar{\alpha}$ and $\bar{\phi}$ from measurements the procedure to compute velocity using values of β, $\bar{\gamma}$ and δ measured in an unknown flow was:

1) Assume $\phi = 0$

2) Calculate the right hand side of equation 6 = $\bar{\gamma}'$

3) If $\left|\bar{\gamma} - \bar{\gamma}'\right| \approx 0$ then a solution for ϕ was found. Proceed to calculate M.

4) Calculate $\partial \gamma / \partial \phi$

5) Set $\phi = \phi + \dfrac{\gamma - \gamma'}{\partial \gamma / \partial \phi}$

6) Return to step 2 with the new value of ϕ

Repeat the iteration until a solution for ϕ was found

To calculate M:

7) Calculate the right hand sides of the equations (9) and (11).

Compute the average = $\bar{x}$.

8) Assume a starting value for M

9) Calculate x using equation (8)

10) If $|x - \bar{x}| \approx 0$ then a solution was found and the unknown flow was determined

11) Calculate dx/dM

12) Set $M = M + \dfrac{x - \bar{x}}{dx/dM}$

13) Return to step 9 with the new value of M

Repeat the iteration until a solution for M was found.

This method (method III) for calibration of the Dodge probe was tested using data previously obtained with the Dodge probe in a known flow. Calibration methods I and II were used to reduce the same data to pitch angle and velocity magnitude. (Each data point corresponded to values of pitch angle and velocity magnitude which were controlled and known during the calibration test.) Table D-1 is a comparison of the accuracies achieved using the three methods.

It can be seen that method III was the least accurate method of representing the calibration of the Dodge probe. However, the mutual interference of the probe tips is probably the cause of the large error. In the 2 probe system of velocity measurement there can be no interference between probes and hence this method should be further considered for that application.

		MACH NO.		PITCH ANGLE	
MACH #	CALIBRATION METHOD	AVG. ERR %	MAX ERR %	AVG. ERR DEG	MAX ERR DEG
.35	I	2.6	3.2	0.5	-0.9
.35	II	0.5	-1.2	0.6	-1.0
.35	III	4.5	7.3	0.8	-1.1
.44	I	1.5	-2.2	0.4	-1.0
.44	II	0.3	-0.6	0.4	-0.6
.44	III	4.7	8.3	1.0	-1.4
.49	I	2.0	-4.2	0.6	-1.8
.49	II	0.5	0.9	0.4	0.7
.49	III	4.9	8.4	1.4	-1.6

Average and maximum values of the errors are shown for the five pitch angle settings -5°, 0°, 5°, 10° & 15°.

TABLE D-1 SUMMARY OF ERRORS IN THE USE OF THREE CALIBRATION METHODS FOR THE DODGE PROBE

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